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The American Journal *of* Physiological Optics

A QUARTERLY JOURNAL

Edited by

CHARLES SHEARD, PH. D.

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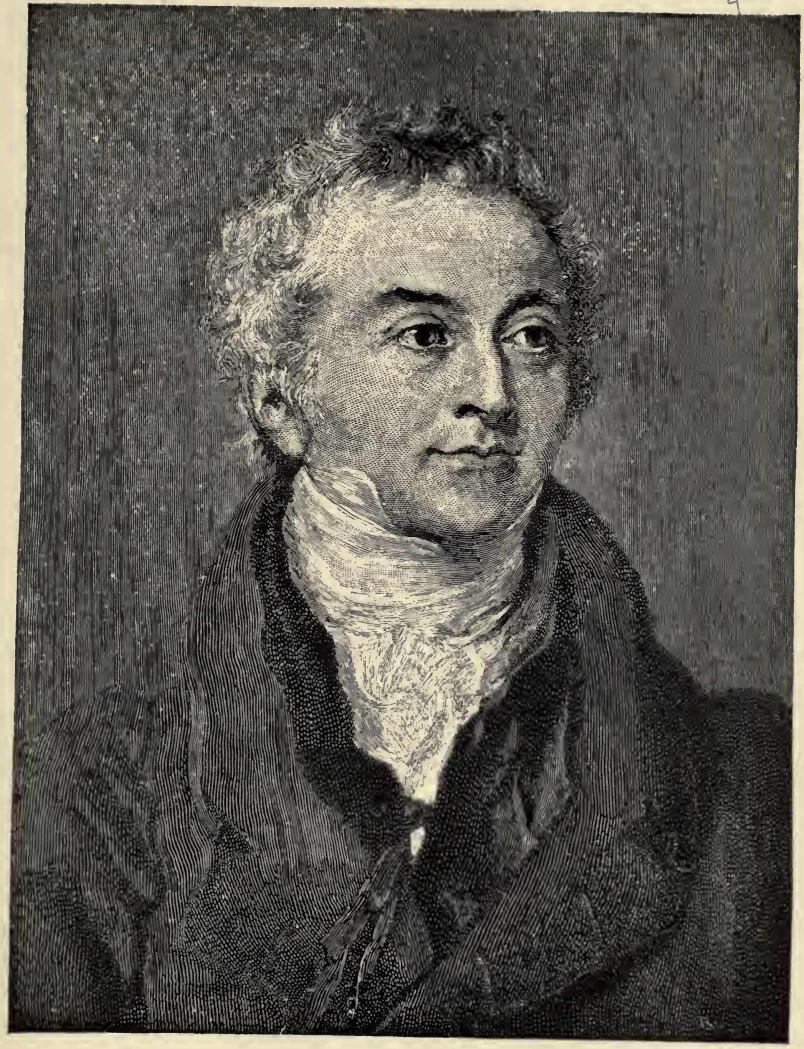

Thomas Young, M. D., F. R. S.
Born June 13, 1773, Milverton, England.
Died May 10, 1829, London, England.

The American Journal *of* Physiological Optics

This Journal

SOME wise man, whose name we have forgotten, said: "Of the making of books there is no end." If he had lived in this day and generation he would not have taken occasion to make this remark in just the form he did, for paper and print, the artisan's skill and the outpourings of men's minds have brought it about that "of the making of books on any subject there is no end." Thank Heaven that such is so—for progress is measured by the interchange of ideas and the printed page has never been and doubtless never will be superseded in this capacity. And magazines and journals are withal *books*, paper-covered though they be.

And so this *Journal* goes forth as another book to become a part of the endless chain of progress. These pages and others which are to follow go out enclosed in a cover bearing the words *American Journal of Physiological Optics*. The title is significant in that it is attached for the first time, in so far as we know, to a journal or magazine devoted solely to the realm of physiologic optics.

The definition of a subject must, in large measure, control that which is or shall be embraced in its content. Very properly, therefore, we may ask the question: What is the field of physiological optics? In the answering of this query will be defined and set forth the scope of this *Journal*. No hard and fast dictionary definition will suffice. We could name its subdivisions and thereby describe it, but they are rather numerous. To us, therefore, *physiological optics* is a science which touches, on the one hand, the highest *philosophic* problems of the human mind and, on the other, keeps in touch in an intimate manner with the work of those who, in their study of the normal and abnormal functionings of the human eye and in the remedying of the defects thereof, must be guided by its fundamental principles. The range of subject matter is a wide one, approaching closely at times the physiological side and at other times the physical side of vision. And like every other science, the older it grows the more it branches.

The purpose of this *Journal* is expressed in a few words. It is to serve as a carrier of knowledge on important phases of optics as applied to visual problems, to stimulate further development and research along such lines and to correlate and join up those findings in allied fields which may serve it and which may open up new and unexpected avenues of approach. To this end some of the articles in this *Journal* will partake of the nature of original research papers, while others will be résumés of important phases of visual optics. The subjects treated and discussed in either manner will be of a varied character in the hope that all readers scientifically interested in problems pertaining to vision and all that this term connotates, as well as topics germane thereto, will find something of value and of interest.

The policy of this *Journal* is embodied in the expression: Science for the sake of Science—Truth for the sake of Truth. We do not and never will know the absolute truth about anything, but we can all be searchers after the Truth. A great man said: If God should offer me Truth in the one hand and the Search for Truth in the other, and should give me my choice I would choose the Search for the Truth. The policy of this *Journal* is thus simply stated: it is our desire that the material which appears within its covers shall contribute to and be helpful in the search for Truth in those matters in which we are interested. But the truth is not always seen or discovered from just one angle or viewpoint. Instance Thomas Young and his heretical departures from the Newtonian theory. So we shall not arrive at the truth, *i.e.*, that which is the most serviceable and most productive of good, if we all continue to follow along the old beaten paths. Hence it is to be hoped that each reader of these pages will from time to time find something with which he radically disagrees because, thereby, he may be led to look further and deeper.

The words *Science* and *Truth* stand for nothing unless they stand first, last, and always as the embodiment of that which has been proven good and found reasonably sufficient and adequate and in advance of previous notions and practices. This is the balance upon which all things must be weighed. Personalities as such are non-existent in science: scientific minds never know cult, or creed, or sect, or nationality, Surely we are all members one of another!

To the end, therefore, that we may become deeper searchers for the Truth, knowing that in the search for this Truth we shall be the better able to serve our fellow-man and advance the cause of science as applied to the preservation and conservation of vision, this *Journal* goes forth from our presses carrying with it the desire of our hearts that it may serve the purposes for which it was founded.

Monuments Not Builded of Stone

MONUMENTS have been created and built since the day that God created man in His own image, when He took of the dry dust, the *admah* and breathed into that dust the breath of life and made man a living memorial of Himself. The dual-natured Jacob in his sojourneyings dreamed a dream as he lay with his head on a pillow of stones and saw a ladder reaching from Heaven to earth and angels ascending and descending. And in the morning he arose and set up a pillar, "even a pillar of stone." He erected this pillar of stone to be a memorial to mark a great event in his own personal development. From the creation day to the present men have erected many memorials, some tangible and some intangible, to be mute reminders of the living, inward progress achieved.

And our men and women of science have dreamed dreams and have had visions; they have, like Jacob, seen the ladder reaching from Heaven to earth with the angels ascending and descending, and in the morning's light they have arisen and labored in the vineyard of truth. They have, by their labors, all unknowingly and unconsciously, erected temples to their glory and monuments to the perpetuation of their names. But the monuments have not been in stone: rather have they been the products of their own minds and of their own hands left to us in the printed word. And not only have such men as Young, Arlt, Airy, Donders, Knapp, Newton, Helmholtz, Bowman, Brewster, von Graefe, Javal, Listing, Maxwell and many others who have joined the "innumerable caravan that moves to the mysterious realm" bequeathed their works as their memorials but they have endowed the succeeding men of science with the spirit that actuated them. These men have, by their lives and their works, perpetuated the true spirit of science—the search for the truth.

This *Journal* cannot be dedicated to these men: it would be far too insignificant to offer such in dedication. It cannot be dedicated to the memories of such men for, while not living, yet are they not dead. Such a dedication would be meaningless. But it can be dedicated and is dedicated to those men and women who—each in his or her own little corner—are striving to contribute their fragments to the great volume of Science and who are, amidst their outgoings and their incomings and their interminglings with fellowmen, devoting their lives to the perpetuation of science through their teachings, their practices and their experimentation. For out of these teachings, these practices and these investigations are made the monuments not builded of stone.

Thomas Young

The Father of Physiological Optics

Charles Sheard, Ph. D.

THE greatest tribute that can be paid the life-work of any scientist is that his labors be considered of such importance as to warrant the affirmation that he was the founder of a branch of human knowledge. Surely no monument of stone or tablet of bronze or even burial in the resting place of kings can equal the appellation of Father bestowed by succeeding generations! Such, indeed, is the lot of but few mortals. But it came as a just reward to Thomas Young—the same Thomas Young whose originality led him away from the old Newtonian theory of light to perform those simple yet wonderful experiments on the interference of light but to be ridiculed and laughed out of court by the then great Lord Brougham. Just think of it: to be forsaken by all to the point of being unable to sell but a single copy of an answer to the harpoonings of a Brougham. But Arago and Fresnel discovered him and his work during the days of his earthly sojourn and Thomas Young did not die in obscurity.

This man in 1793 explained the mode in which the eye accommodates itself to vision at different distances as dependent upon the changes of curvature of the crystalline lens; in 1801 he discovered the defect known as astigmatism; in his lectures he put forth the theory, afterwards developed by the versatile von Helmholtz, that color perception depends on the presence in the retina of three kinds of nerve fibres which respond respectively to red, green, and violet lights. The first correct explanation of accommodation, the first recognition of astigmatism, the first plausible and possibly most commonly accepted theory of color vision—these surely entitle Thomas Young to the appellation of Father of Physiological Optics. Anyone might well be delighted if he or she could perform just one piece of investigational work of as much consequence and importance and of as much permanence.

Thomas Young was born an Englishman and into a family of the Society of Friends; he wore the dress peculiar to this sect in his younger days but later on abandoned it. Of his precocity of mind there are many stories. Tyndall relates that he could read quite well when two years of age and that he had read the whole Bible twice, from one end to the other, by the time he was four years of age. Like many another person forced from childhood up to conform to a system of education devised for the average pupil, he seems to have profited little by regular schooling and it is said that he frequented many schools and surpassed not only his schoolfellows but also his masters. When a dozen years of age he became interested in botany and found that he needed a microscope. But Young did not buy one—rather a treatise on optics and a lathe in order to grind his own lenses. This boy of a century and a half ago differed considerably from the average youth of that day or this, for he bought the treatise on optics first. While reading the work on optics he met with fluxional symbols, so he must needs introduce himself to the methods of fluxions in order to understand the references in optics. And it grows really astonishing when we learn that, during his boyhood days, he became proficient in Latin, Greek, French, Italian, Hebrew, Persian, and Arabic.

At a very early age Young became the tutor of the grandson of a rich gentleman of Youngsbury. For nearly five years he remained in that capacity and was again his own tutor while tutoring others. He divided his time between classical studies and higher mathematics, especially optics and the *Principia* of Newton. We may be pardoned the digression when we note that Young did not hesitate to engage in an all-round general training without worrying his brain as to the immediate value of the classics in terms of the pound sterling and the shilling. And again, he studied the mathematics of optics. Our practitioners of these days and of the days to come need more of the solid foundation of the mathematics of optics!

With this splendid foundation training the youthful Thomas entered upon the study of medicine. And today we, too, are swinging back to a realization of the fact that a reasonable number of years of training in languages, mathematics, and science are requisite for the future practitioner. So, in 1792, Young began his medical studies with his uncle in London and then continued his studies at Edinburgh and at Göttingen. Upon his return from the Continent he went to Cambridge and obtained the degrees of Bachelor of Physics and Doctor of Medicine. In 1800 he established himself as a practicing physician in London and continued this practice through the whole of his life. But we are told that he never had a great clientele, for his patients considered him too learned. During his early years as a practitioner he accepted the position of Professor of Philosophy at the Royal Institution. These lectures were later published in two immense quarto volumes treating of almost all phases of physics.

That which gives interest to the study of his life is his extraordinary scientific activity. First, we have his celebrated paper *On the Mechanism of the Eye* (1801). This, together with other works of Thomas Young, forms the true basis of the science of physiological optics. Then we have his three papers on *Sound and Light* in which he abandoned the Newtonian theory of light, accepting instead the more ancient theory of Huyghens which considers light as the product of vibrations in the ether, and applying to it his celebrated principles of interference. But the crushing ridicule of his work by Brougham led him to refrain from writing on optics for years; he wrote on the construction of ships, on an algebraic expression of the value of life, on tables of mortality and many other topics in which his astonishing mass of knowledge and great originality were evinced. But, in 1815, a French engineer, Fresnel, sent to the Academy of Science at Paris a paper on *Diffraction* in which, independently of Young, he applied the theory of interference. On reading it the French physicist Arago remembered Young's papers and showed them to Fresnel. Fresnel recognized the priority of Young. The frequent references to Young's writings in the immediately succeeding years called attention to him and he became famous. This recognition encouraged him to return to the study of optics, and in 1817 he wrote the article on *Chromatics* for the *Encyclopedia Britannica* and in this essay he made a very important addition to his theory. And in the course of a little more than a year he wrote his article on *Egypt*, remarkable for laborious and original research, the principal object of the paper being the interpretation of the famous Rosetta stone.

Although there are many other excellencies to be found in his works, we may say that Young has three great achievements in physiological optics. His first discovered the error of the human eye that is now known as astigmatism; he found that the accommodation of the human eye is produced by an increase in the curvatures of the surfaces of the crystalline lens, and he showed that all our color sensations may be considered as composed of three simple sensations, red, green, and yellow, and that color blind people have, in general, only two of these.

In order to determine the refraction of his own eyes Young used his optometer, an instrument based on the principle of Scheiner's experiment. Of this instrument Tscherning says: "It appears to me to be one of the most important instruments for the study of physiologic optics." With his device Young determined the refraction of his eye to be a myopia of four diopters combined with an astigmatism of about one and three-quarters diopter against the rule. By putting his eye under water he found that this astigmatic error was not due to corneal curvature differences; hence, presumably, the ophthalmometer, had such an instrument then existed, would have shown little if any difference in various meridians. From these early experiments as a starting point have come the researches of Airy, Helmholtz, Donders, Knapp, Javal, Schioetz, and those of the later generation.

Young's paper on the mechanism of the eye was written especially to prove that the accommodation of the eye for short distances is produced by an increase of the curvature of the lens. His paper did not produce any effect at the time. For as late as 1851 Arlt, having proved that myopia is due to an increased length of the eyeball, concluded that accommodation was also produced by virtue of a slight lengthening of the eyeball. It remained for Cramer in 1853, using the discovery of Purkinje that images could be produced by reflection at the surfaces of the crystalline lens, to observe that the image due to the anterior surface grows small and approaches the axis when the eye accommodates. And Helmholtz at about the same time presented his theory of accommodation. Young never determined the actuating agent in accommodative changes, for it was not until the '40's that Bowman in England and Bruecke in Germany found the ciliary muscle. But Young did, by the process of elimination, arrive at the fact that the curvature changes of the crystalline lens must be the seat of accommodation. By very subtle experiments Young showed that the length of the axis of the eyeball does not change during accommodation. Another series of experiments showed that the cornea did not change in curvature. And again, by putting the eye under water, he found that the power of accommodation was not diminished, although the action of the cornea was excluded. The only explanation remaining was the one at which he arrived and which he demonstrated to be correct by the proof that some young subjects who have been operated upon for cataract had completely lost the power of accommodation. By further observations he determined that the accommodation is much stronger in the center of the pupil than near the margin, and Young endeavored to calculate the conical form of the surfaces during accommodation. These experiments of Young led to the subsequent famous work of Tscherning using the ophthalmophakometer.

Young's ideas on color-sense have an importance equal to that of his other conceptions. Clerk Maxwell gave the experimental proof that three spectral colors can be so chosen that all the existing colors can be reproduced almost exactly by a mixture of these three. On the Continent Young's theory was quite unknown until Helmholtz adopted and modified it and the theory became known as that of Young-Helmholtz.

These brief comments ought to give some idea of the extraordinary extent of Young's mind. He himself tells that during his last visit to Paris he went to the Institute one Monday and had the great pleasure of hearing the members of the Academy of Science discuss some theories of optics based on his own researches; then he went there on another day and heard the Academy of Inscriptions discussing some of his hieroglyphical discoveries. And, as Tscherning once so aptly said, "It might very well have happened that he should have heard a discussion on his theories of life assurance in the Academy of Political Science or a discussion of his theory of music in the Academie des Beaux Arts, or even a discussion of his studies on the heart and the arteries in the Academy of Medicine. I think that the world has never seen anything like it." And, for one, we are delighted that Young lived to see his work appreciated. For even scientific minds and the brains of geniuses are enclosed in the ordinary sort of cases—they are all human. And to be recognized and appreciated is a veritable Balm of Gilead—it often causes two ideas to take form where but one existed before. And of what use are the flowers anyway when one is dead and gone!

Eyestrain in its Relation to Occupations

George M. Gould, M. D.

EYESTRAIN is an unfortunate word, but we are compelled to use it. It is usually misunderstood to mean the overuse of a pair of optically perfect eyes. It should be defined as that use of ametropic eyes which is pathogenic, or productive of local or systemic derangements. But measurements of human eyes demonstrate that there is not, probably, one pair in the world absolutely emmetropic—that would be a miracle which Nature with all her infinite ingenuity has never performed. No human face, indeed, of the world's sixteen hundred million may be held perfect, either artistically or physiologically. To the owner of the face this is relatively an unimportant matter, but to the owner of the pair of eyes, an error of one three-hundredth of an inch in the curvature or dimensions of the eyeballs may make their all-important function pathological.

The most highly differentiated tissues of the human organism lie in the brain, and genetically the eye is the only organ made directly from cerebral tissue. The brain, literally, comes out of the skull in order to see. The eye responds to the smallest physical force in the world—that is, light-waves are hundreds of millions of millions of times more infinitesimal than sound-waves. The eyes are the hardest worked of all the organs. The safety and existence of human lives frequently depend directly upon their accurate function, *i.e.*, upon non-pathogenic action. All organismal motility is conditioned upon mathematically exact coördination with and dominance of vision in the motions and localizations of the hands and feet, of external and distinct objects, etc. The perfection of visual function requisite in civilized occupations of infinite variety and differentiation is thus seen to be necessarily wanting in some way, or at some time of life. The startling truth comes to better recognition when we realize that in the past the entire complicated mechanism of vision was made and used almost solely for distant vision, while for the majority of its expert and educated workers, modern civilization chiefly and increasingly demands constant and accurate vision at near range. For this the mechanism does not exist, and the attempt to compel the function brings disease.

This strange and unscientific neglect is explainable by the failure of investigators and physicians to recognize two physiological truths:—Nature cannot keep a muscle continuously innervated or contracted, and she cannot keep a retina continuously sensitized during any protracted exhaustion by the image-stimulus. Of the ciliary muscle of the eye, and for most of the working day, modern tasks command almost continuous innervation and contraction. So exigent is the task-master that the eyes are put to impossible tasks, from which result, first, local inflammation and morbidities of the lids, conjunctiva, etc., and, later, retinal congestions, myopia, iritis, cataract, and so on. Worse even than these, are the systemic ocular reflexes, the morbid overflows and reactions of the cerebral telegraphic switchboard. There is a long list of these cerebral and mental diseases, the vast majority not caused by organic disease of the brain, and due solely to the morbid reflexes of eyestrain—"nervousness," tics, choreas, neurasthenias, epilepsies, and especially the interminable list of headaches and migraines—with or without giddiness, swoonings or faintings; exhaustion and morbid psychic effects; diseases of memory such as losses of self-knowledge and subsequent findings of self far-away with sudden coming-back of memory; so called Meniere's disease; the functional stomachal and digestional diseases with persistent vomiting, anemia, denutrition, etc. Lastly, to swell and complicate the horror, between 80 and 90 percent. of the school-educated have lateral spinal curvature, which is largely of ocular origin.

All these amazing sins of Unhygiene are almost wholly preventable by two very simple devices—by scientific spectacle-lenses, and by physiological posture of the head and body, especially during writing, study, etc. This correct posture may only and chiefly be secured by the sharply-slanted school desk leaf, and proper position of the writing-page and book, the placing of the hand, etc. The spectacles may be obtained only by great scientific care, and when science is doubled by philanthropy. The morbidity-rate will then be several times reduced, and the mortality-rate at least halved.

In 1910 the Census Bureau listed some seven or eight thousand separate and distinct occupations. Classifications according to morbidity and mortality rate are almost impossible. I have, therefore, grouped modern workers in such a way that we may roughly estimate the comparative incidence of a single pathogenic factor according to the nature and the conditions of the labor. The five groupings of occupations are designed to indicate their rôles in creating or increasing the diseases and derangements directly or indirectly due to eyestrain.

As a rule, the least eyestrain will be found in those workers of Group I, the most in those of Group V. From number 1 to 114 eyestrain reflexes and diseases will generally be found to increase *pari passu*. The most common mistake of all investigators and physicians is to forget the unity of the organism and the interdependence of its individual parts and organs. Hence the thousand-fold and daily repeated error of considering symptoms manifested in one organ as if it were independent and solely affected, while the cause of the disturbance really lies in some distant organ. Just as a poison in one part of the body morbidizes all other parts, as a lesion in a distant nerve or ganglion may affect a far and unlike organ and function, so may malfunction of the eyeballs beget disease in brain, stomach, spinal column—wherever, indeed, errant neural forces come into relation with movement, or the world of circumstance and demand. It is an old fashion to ignore this truth, but the fashion must change if our philanthropy is to be made real love of men and if science is to be made really scientific.

The groupings of various vocations and occupations in the order of their eyestrain reflexes and diseases follow:

GROUP I

(40 Percent. of Population; 1 to 20 Percent. have Ocular or Eyestrain Diseases)

1. Hunters, Trappers.
2. Lumbermen, Raftsmen.
3. Fishermen, Oystermen.
4. Seamen, Sailors, Marines, Navy.
5. Ranchmen, Herders, Drovers, Stock-raisers.
6. Farmers, Agricultural Laborers, Fruit-raisers.
7. Common Laborers, Road and Street-makers.
8. Soldiers.
9. Teamsters, Draymen, Hackmen, Hostlers, Hucksters.
10. Policemen, Watchmen.
11. Street-railway Employees.
12. Firemen, Overseers.
13. Gardeners, Florists.
14. Packers of Meat, Fruits, etc.
15. Switchmen.
16. Hod-carriers, Building and Construction Workers.
17. Railway Trainmen, Carmen, Freight-handlers.
18. Stationary Engineers and Firemen.
19. Quarrymen, Ore-men.
20. Locomotive Firemen.
21. Locomotive Engineers.

GROUP II

(10 Percent. of Population; 20 to 40 Percent. have Ocular or Eyestrain Diseases)

22. Sugar-makers and Refiners.
23. Hotel and Restaurant Employees and Waiters.
24. Engineers (Civil, Mechanical, Electrical), Surveyors.
25. Railway Conductors.

26. Domestic Servants, Cooks.
27. Laundry Workers.
28. Roofers (Composition, Slate, Tile).
29. Bill-Posters.
30. Painters (Outside).
31. Brick and Terra-cotta Workers.
32. Pottery and Tile Workmen.
33. Asbestos Workmen.
34. Brewery Employees.
35. Stage Employees.
36. Butchers, Meat-cutters.
37. Pulp, Sulphite, Paper Workers.
38. Steel-plate Transferrers.
39. Marble Workers.
40. Carriage and Wagon Makers.
41. Piano and Organ Workmen.
42. Wood-workers, Curtain-makers.
43. Carpenters, Joiners, Car-makers, Pattern-makers.
44. Cement-workers.
45. Merchants, Salesmen, etc.

GROUP III

(10 Percent. of Population; 40 to 60 Percent. have Ocular or Eyestrain Diseases)

46. Masons, Stone-Cutters, Bricklayers.
47. Printing Pressmen, Lithograph Press-Folders, Stereotypers, etc.
48. Plumbers, Gas-Fitters, Steam and Hot-Water Fitters.
49. Machinists.
50. Painters (inside), Decorators, Paper-hangers.
51. Lathers and Plasterers.
52. Coopers.
53. Moulders, Foundry-Men.
54. Bridge, Structural Iron, Steel, and Tin Workers.
55. Metal Workers, Iron-Ship Makers.
56. Blacksmiths, Horse-shoers.
57. Lead and Zinc Workers.

58. Paper-Makers.

GROUP IV

(20 Percent. of Population; 60 to 80 Percent. have Ocular or Eyestrain Diseases)

59. Housewives.
60. Professional Invalids, Asylum and Sanitarium Residents, etc.
61. Bakers and Confectionery-Makers.
62. Electrical Workers.
63. Brush Makers.
64. Hat and Cap Makers.
65. Boot, Shoe, and Leather Goods Workers.
66. Actors and Actresses.
67. Upholsterers.
68. Glove-Makers.
69. Spinners, Weavers, Textile-Workers.
70. Saw-Smiths.
71. Garment Makers.
72. Metal Grinders, Polishers, etc.
73. Book-Binders.
74. Basket-Makers.
75. Tool and Cutlery Workers.
76. Pupils of Public and Private schools, below High-School
77. Chemists, Laboratory Workers.
78. Musicians.
79. Telegraphers.
80. Boiler Makers.
81. Broom Makers, etc.
82. Miners (Coal, Mineral, etc.).
83. Tunnel and Subway Workmen.
84. Compressed-air and Foundation Workmen.

GROUP V

(20 Percent. of Population; 80 to 100 Percent. have Ocular or Eyestrain Diseases)

85. Students of High-Schools, Seminaries, Colleges, Universities.

86. Clergymen.
87. Lawyers.
88. Bank Clerks.
89. Lathe Workers.
90. Clerks, Commercial, P. O., Ry.
91. Wood Carvers, Lithographers.
92. Journalists, Reporters.
93. Authors, Literary, Scientific, etc.
94 Professors, Teachers.
95. Barbers.
96. Stenographers, Typewriters
97. Draughtsmen, Designers, Architects.
98. Physicians and Nurses.
99. Artificial Flower Makers.
100. Jewelry Makers.
101 Bookkeepers, Copyists.
102. Dentists.
103. Watch and Clock Makers.
104. Telephonists.
105. Engravers and Photo-engravers.
106. Cigar Makers.
107. Glass Blowers.
108. Sewing Women and Men, Dressmakers, Tailors.
109. Lace and Embroidery Workers.
110. Typesetters.
111. Cutting Die and Cutter.
112. Miniature Painters, Etchers, etc.
113. Proofreaders.
114. Diamond Polishers.

The groups and the order given to the occupations within a group have the value only of my guesses, made up from personal experiences with patients, supplemented by reading and individual knowledge of medicine, industries, and life. The large percentage of the total population placed in Group I appears justified by the inclusion of the great masses classed as Farmers, Agricultural Laborers, Soldiers, Railway Workmen, etc. The school children and housewives greatly increase the total comprising Group IV.

Assignment of a person to a group, or to a particular place in a group, depends upon a number of considerations, the chief being:

1. The average distance from the eyes of the object habitually observed—the nearer it is the greater the eyestrain.

2. The more constant this near focalization the more severe the eyestrain.

3. With decrease of the illumination below a high physiological standard there is a geometrical increase of eyestrain.

4. The exposure of the eyes, during labor, to wind, cold, heat, dust, excessive illumination, etc., heightens their liability to inflammatory diseases, and also to eyestrain and its systemic reflexes.

5. In near-work such as reading, writing, etc., any habitual abnormal position of the head or of the body may add enormously to the ocular injuries and eyestrain.

6. The age of the workman may govern the degree of eyestrain. Without correcting spectacles everyone has eyestrain after 43 years of age, especially in looking at objects persistently within "near range," *i.e.*, at reading, writing, and handwork distances.

7. The synchronous coöperation of the two eyes is also an important factor. By midlife, because of anisometropia, heterophoria, etc., one eye is often disused, amblyopic, or even blind. This trend emphasizes dominacy of one eye, so that this lessens eyestrain, which is the cause of the disuse of the eyes, but at the same time it adds to the liability of accident from the blind side, and also multiplies the dangers and handicaps of the worker in other respects.

8. Probably six percent. of children are naturally left-handed, left-eyedness causing left-handedness. The un-

conscious crime of trying to make a left-handed child into a right-handed one produces tragedy in the life. Many causes may also transfer the dominance of the coördinating eye over to the other eye, thus exposing the unfortunate person to many trials and dangers.

9. A peculiar axis of astigmatism, or the writing posture may so tilt the head and body to one side as to set up lateral spinal curvature, and bring the child to death's door because of vomiting, denutrition, etc. Correction of the refraction errors and the morbid posture in such cases would bring health. From 6 to 10 years of age many children show an incomprehensible "nervousness," chorea, fickle appetite, and various disorders, very frequently due to eyestrain.

10. There is one qualification as to the constancy of the groupings, which, if omitted would confuse the investigator. It is the unsuspected eyestrain work which may be indulged in besides that of the occupational demand. A member of Group I, for instance, may be ruining eyes and health by novel-reading, study, sewing, embroidery, or games, etc., carried on at night, or during rainy or unseasonable weather. The light used may also be poor and unshaded, in front of the eyes. The habits must be studied to learn the truth about each individual worker, and his proper placing in one group or another. I have known of hundreds of patients with health nearly or wholly ruined by eyestrain, who, face to the light, were reading without spectacles, and lying down, too, for many hours a day, or so long as outraged nature would permit.

Although the order of the groups was not designed to illustrate one thing, it nevertheless does make manifest a noteworthy fact: the production of eyestrain by recent civilization. The first group includes most of those occupations dominant before the invention of printing. In the last group they are almost solely made up of the most differentiated or specialized callings of the latest civilization required by learning, literature, printing, sewing, telephoning, and their ancillary crafts. Intimately correlated is the fact of urbanization. Eyestrain increases *pari passu* with work at near-range; *i.e.*, according to the amount of work done inside of the house, and the modern growth of population is largely taken up by the town and city. Some part of this evil is offset by the invention and popular use, in the last few years, of glass windows,—the greatest of all discoveries as regards health. And almost as valuable is the better artificial illumination of our time. The rush lights, lard lamps, and tallow-dips of our forefathers and foremothers were prolific sources of ruined eyes and health. For this reason, in India to-day cataract is vastly more prevalent than with us.

Civilization thus necessarily lessens the numbers in the lower or first groups. All civilization depends upon increased use of the eyes at near-range. Group V is thus steadily absorbing the members of the lower groups. There are, indeed, a small number in Groups IV and V who are really going back to preceding groups by a sort of vicarious atonement. For instance, heads of business enterprises and of various institutions, and many professional men, now employ stenographers, research-workers, clerks, copyists, even authors and bookmakers, etc. These come up from lower groups and take upon themselves the ocular reflexes of their employers. Machinery is also lessening the number of employees of the first four groups, and in the differentiation of function and systematization of many businesses the same fact appears. Urbanization itself increases the number of sedentary or eye-straining occupations. The school children and students with the sharp general increase of the number of the educated, coupled with the amazingly vast output of the printing press—these and various other similar habits add to the evil.

Every advance in civilization is dependent upon greater precision and increased strain in near-range vision. There is thus the progressive moving up of the members of each group from the lower to the higher, and a rapid increase of the percentage of Group V. The added fact that, in the vertebrata, all useful actions, all motilities, all muscular actions and coördinations, have depended upon vision—vision, both as incitor and director—shows the whole fact and course of animalian and human evolution to be dependent upon vision and to be largely the product of vision. The exclusion of the unfit and the survival of the fit has been and is rigidly conditioned upon the inheritance of the best eyes and the highest accuracy of function of the eyes. It should be recognized that the pathological functioning of an organ has for the organism the equivalent of ill which its physiologic function has for good, or of service. The pathology, *i. e.*, the ill-health of civilization, is in truth largely due to the pathology of vision. Learning to see and to coördinate vision and muscular action, with precision and lightning-like rapidity, requires a long and difficult apprenticeship. It absorbs at least a dozen of years of the child's life. If handicapped by ametropia the result is never good; with many defects it is so imperfect that it begets constant pathologic results both to eyes and organisms. As to the millions of common school-children, their ocular ill, their eyestrain, and their effects upon general health, their standing in classes, the reasons for the dullards and truants, and even juvenile criminals,—of all this big book of human ills and wrong we are now at the opening page. The headings of the chapters on left-handedness, spinal curvature, and the writing posture have been written, but not one good school desk exists in the United States, and every child writes with body and head and eyes in disease-producing postures.

There are three sources of sickness; either the workman's body or mind brings it with him; or his job and its conditions supply it; or lastly, it is due to far-coming infection. We now know that the seed, infection, is of comparatively little power or significance without the conditioning and prepared soil. The latest word, moreover, of medical science,—immunity or immunology,— shows that the best way to meet infection is by the inherent and strengthened ingenuity of wise Life to fight the invading foe in her own sacred home and country. We are thus practically limited to two sources of our morbidities: Disease is either brought to his occupation in the body of the worker, or the occupational conditions beget it.

But in its early stages, the ontogeny is simply the epitomized result of phylogenetic action and reaction in the infinite evolutionary past, and it is therefore but little subject to the temporary influence of individual therapeutic effort. Moreover, the later and the fewer the parental links of the phylum, the less this modification of the ontogeny. Effective therapeutics therefore resolves itself almost wholly into late and cumulative ontogenetic modifications and resistances following environmental changes. Whether these characters are called "acquired" or not, and whatever may be the definition of "acquired," matters naught to one who fixes his attention upon real facts and effective function instead of upon theories and definitions. The thought which brings clearness into the discussion is this:—The longer the phylogenetic history, and the more differentiated the ontogenetic tissues, the less the reaction to and modification by circumstances. The plant which, taken from low levels to mountain heights, lives by sudden and extensive modifications of structure has little to teach the highly differentiated ontogeny called a man. He must prevent sickness and preserve life largely by the artificial helps of civilization and science instead of by crude structural changes.

The conclusion thus becomes clear that environmental injuries may be prevented, neutralized, or overcome in three ways:

1. By our conscious and designed environmental changes made possible by civilization, through devices, new mechanisms and controlled conditions. By experience and instruction the workman may be taught to avoid his reckless occupational poisonings; machine-holing will bring miners'

nystagmus to an end; glass-blowers' cataract is unnecessary; most infectious and parasitic diseases are conquerable by hygiene, almost by simple cleanliness alone; poisonings by the work in lead, brass, mercury, etc., may be easily avoided; eyestrain is prevented by scientific spectacles; and so on through the list. When once combined and in earnest, hygiene, civilization, and philanthropy will largely extinguish occupational disease by such protective modifications of conditions. Already the life-length and health secured by modern clothing, housing, glass-windows, artificial illumination, progressive farming, transportation, etc., have enormously added to the number of lives and to the average length of life of civilized peoples. The ametropic eyeball, for example, cannot be made emmetropic, but the ametropia may be neutralized by lately devised optical lenses.

2. By increasing, through artificial immunization, the natural or acquired resisting powers of the body against infection.

3. By slow and cumulative reactions, functional, cellular, or structural, perhaps by Eugenics, against harmful environmental influences. This cumulative modifiability in phylogenic development has been the mechanism of the origin of species, and of filling the world with life.

The abiding result either of simple observation, or of the most inclusive scientific generalization, the one great miracle of all Life, is this amazing success in the intelligent adaptation of long lines of inheriting organisms to an infinitely varied and continuously varying environment. These diverse life-forms and the origins of species are simply illustrations that the origins of disease may finally be neutralized or overcome. This is the glory and the success of rational as distinguished from empirical therapeutics, the task of preventive instead of curative measures. Pathogenesis being thus due to the failure of reaction of the organism, it follows that the occupation may be freed from its apparent morbific effects either by the hygienic suggestions of the hurt organism, or by over-coming and preventing the hurt through its own self-evolved variations, obviations, adaptations, resistances, immunizations, and victories. Temporary, that is, functional diseases, are the passing failures of the organism to react successfully; organic and lethal diseases are the ingravescent failures, or postponements of death; and death itself is the final acknowledgment of utter failure to react successfully.

What disease-breeding factors and powers does the worker bring to his occupation? It is self-evident that, except infections (and even here the organism supplies the most important help, the soil), all organic and lethal diseases (omitting utter senility) have their sources in abnormal or aberrant physiology. The pathology which is rational and motived upon philanthropy asks simply about the precedent pathogenic and curable functions that begot the incurable disease. They are the causes of the lethal diseases; death, as we have said, being the confession of the individual inability to adapt the organism to the environment. The command is therefore to stop the late and incurable diseases by the prevention and cure of the functional diseases. In eyestrain this is amazingly possible. Now, there are a hundred types of these preventable functional diseases. But their ultimate causes are not so many. Our world, for instance, is crazed and sickened by morbid habits, by alcohol, by tobacco, by sugar and candy, by luxury, by narcotics, by venereal diseases, by pseudoliterature, by pseudoeducation, by egomania, by sin, by the lust for power and wealth, by concealed crime, by faddism, by monotonous drudgery, by diseases the prevention of which, or the causes and cures of which, are known but ignored, by hopeless poverty, by the haunting horrors of insanity, suicide, and approaching death. The chief and most prolific of the list is eyestrain, but its known rôle and certain prevention are sadly neglected.

Up to the present time, the recognized occupational diseases of the eyes have been few in number, the etiologies indefinite or erroneous, the prevention and therapeutics mere makeshifts or unknown. This was because the physiology of vision was not understood, the facts and causes of eyestrain unrecognized. Many years ago, for example, with little search, I found all about me large numbers of albinos. The results of the study of these cases were most inspiriting to me but to nobody else. There may be 100,000 such patients, or should-be patients, in the United States. Their tragedy is solely ocular and wholly due to non-pigmentation of the irises. The whiteness of the hair, etc., has no significance. Because of the semi-transparency of the irises the entire retinas are flooded with half-light, the image thus not sharp or accurately delimited by shadows. The retinal sensitiveness is so exhausted that great amblyopia follows, and, to find new and sensitive retinal areas, a constant nystagmus naturally replaces the steady fixation of the image upon the macula. It was an inevitable and saving way of making the best of a bad bargain. The palpebral aperture is also habitually narrowed in order to exclude the peripheral rays of light, and the cornea is thus crushed by the lids into enormous astigmatisms at axes 90°. The correction of the astigmatism, while not curing the chief cause of misery, would bring wonderful relief to the albino from the worst effect, and would multiply his abilities to overcome his pitiful industrial problems. Except as a farmer—and a poor one—he is now shut out of most every ordinary calling. The poor image not bordered by darkness, which is the real source of the evils, could be stopped by early and constant use of colored or smoked toric lenses with small transparent ametropic lenses inserted in the centers.

The study of albinism would have taught the needed lesson as to the etiology of the nystagmus of the "holing" coal-miner. Its cause is said to be due to the position of the body, and head of the miner in holing and his looking upward. I think this upward looking has little or nothing to do with the origin of the disease, because the nystagmus of the more numerous albinos could not be from such a non-existing cause. I have watched miners at holing, and there was no looking upward, the horizontal body and head not possibly being lower than the point of impact of the pick. The real cause of the miner's nystagmus is, I think, the same as that of the child with anterior polar, or any central, cataract, etc. It consists of the extremely pathologic illumination of the retina by the object gazed at. The bare flame of the wretched lamp is often in front of the eyes. There is also quick, tense closing of the lids to avoid corneal injuries by the darting bits of coal; this increases astigmatism, amblyopia, and eyestrain generally. The change to machine-holing will end miner's nystagmus.

Most suggestive are the three reports concerning telephone operators issued in the United States, in Canada, and in England. There are in the United States about 125,000 telephone girls whose average terms of service are three years or less. The working hours are about eight per diem; the average number of calls is about 140 an hour running "at the peak," to "the breaking point of efficiency," 225 or more. The companies seem to be trying to do their duty as regards the health of the girls. Thousands of dollars have been spent for the operators, and sufficient air-space and good illumination have been secured. Despite these things, it is a startling fact that, altho only young and healthy girls are selected, the average length of service does not exceed three years, and maybe less. The symptoms mentioned are headache, dullness, indigestion, exhaustion, nerve strain, insomnia at night, but with day-time sleepiness, colds, etc.

The intolerable fact that stares at one from every page of the United States Report is that not the slightest hint is given that the two or three short years of telephone labor possible to the girls, and nine-tenths of all their awful suffering and wrecking, is largely due to constant near-range eyework without scientific spectacles. Many of the girls of course change occupations, and for many reasons; often, doubtless, because of the difficulties of keeping health. At all events no blame whatever attaches to the companies. The fault is the general indifference to or ignorance of the nature and consequences of eyestrain.

The report of the Royal Commission of Canada is somewhat more enlightening because physicians from the University of Toronto were called to give their testimony as to the illness resulting from telephone-operating. These gentlemen testify that the following facts, conditions, or diseases exist—I quote their words:

> Reaching upward injuriously affects the nervous system.
> Nervous debility.
> Faces showed indications of weakness on account of strenuous employment.
> Eye, ear, and throat all strained.
> Nervous hysteria.
> Constitution and nervous system injured.
> Wearing down of the nervous system.
> Optic and auditory nerves strained.
> Debilitating to the nervous system.
> Girls burn up more energy than they produce.
> Most exhausting of all occupations.
> Injurious to eyesight.
> Produces headache looking at the holes.
> Prevents rest.
> Cannot sleep when they go home.
> Couldn't eat well.
> Reaching is hard and injurious.
> Eye-troubles, headaches, and nervous troubles.
> Affects the eyes, and through the eyes the general system.
> The most trying of occupations.
> Throat, chest and nervous troubles, and headaches.
> Nervous prostration and nervous breakdown.
> After three years unable to perform the ordinary occupations of womanhood satisfactorily.
> Fainting.
> Strain on nervous system through eye and ear.

Nerve fagged.
Nervous exhaustion.
Strain upon the optic nerve and the muscles of the eye.
Difficulty in fitting the plug in; they seemed to scrutinize it closely.
The nerves governing the extraocular muscles which focus the eye upon the object looked upon are the nerves where the greatest part of the strain comes.
Reaching added to the physical fatigue.
When they leave they turn out badly in their future domestic relations.
It is this sort of thing that is laying the foundations of the asylums, and it is dealing with the question now that will prevent the building of asylums, and the loss of the people to the community.
Not so much physical as mental and nervous, and exhaustion of nervous energy, a depletion of nervous force.
The reason for such a marked increase in insanity and nervous prostration all over the country.
After five years she would be disqualified to become a wife and mother.
On future generations the effect will be epilepsy and all sorts of nervous diseases.

In other words—brave statements of facts and end-results with no recognition of the single cause, ametropia or eyestrain, from lack of scientific spectacles. In all households, in every occupation, in the thousands of hospitals, sanitariums, homes, etc., are millions of sufferers with the identical diseases, and caused by near-work without correcting glasses in every and any occupation.

The English report does not say that the "neurasthenia" is caused by the work but that this, with the "anemia and neurotic tendencies," were brought to it by the worker. "Errors of refraction," it is stated, "became manifest by the nature of the work." The medical officers are advised to exclude candidates "showing pronounced signs of nervous instability or anemia and of ensuring that candidates suffering from hypermetropia and astigmatism have those defects corrected by proper glasses." The committee found that 142 out of 248 operators examined had had their health impaired by the "nerve and physical strain." The disorders most frequently mentioned and most emphasized among the telephonists are "nervous affections, digestive disorders, anemia, nervousness, neurasthenia, nervous disorders, nervous debility, migraine, headaches, vertigo, palpitation." etc.,—precisely those found in thousands of patients, and for twenty-five years demonstrated to be due to eyestrain.

In Norway the report is that of 390 women, there were in one year 11,621 days of sick-absence, many because of diseases (now recognized as due to eyestrain) distributed as follows:

Bronchitis, laryngitis, influenza, etc.	2,482
Gastritis, enteritis, etc.	2,324
Neurasthenia, cephalagia, etc.	1,990
Anemia, circulatory, and blood troubles	1,705
Affections of sight	651

The trials of the telephone girls illustrate the eyestrain-results of new callings of civilization. There are many such novel industries appearing. A friend advises me, for instance, that men who run elevators or lifts are subject to novel eyestrain-diseases. Typewriters, retouchers of photograph plates, machine printers and rulers, wallpaper printers, etc., may be also mentioned. Some other callings are certainly as health-wrecking as those of the telephonists, *e. g.*, of musical composers, literary workers, sewing women, etc. It is gratifying to know that a host of nervous and digestional disorders may soon be recognized as originating in eyestrain.

The oldest treatise I have found on the subject of industrial diseases is that of Halfort, published in 1845. It is the first time that artisans (whose labor is so greatly ocular) are thus emphasized as so decidedly subject to occupational disease. The author, concerning straining of the eyes in industries, speaks of the now forgotten truth that the eyes are the most delicately constructed and noble organs of the body; he emphasizes the reasons for such strains as follows:

1. By long-continued looking at small objects, mentioning especially watchmakers, typesetters, embroiderers, lacemakers, miniature-painters, manuscript-copyists, engravers, etc.

2. Work with harsh colors, or upon highly illuminated objects.

3. Labor under poor or fluctuating illumination, such as by flickering oil or candle lights, and even with good lights if long continued.

4. Sudden change from darkness to light.

The diseases resulting from these abuses are thus listed:

1. Shortsightedness from work on minute objects.

2. Inflammation of the external parts of the eyes, and later of the internal parts, leading to loss of vision and cataract.

3. Visual deterioration, amaurosis, deep-seated pain of the eyes, more frequently intense headaches, etc.

Spectacles and hygienic precautions are recommended to obviate the foregoing ills. The nervous irritability, etc., of yarn-spinners is emphasized. And there, forgotten or ignored, this wise old observer is left.

There are not a few encyclopedic and erudite epitomes of the subject of industrial ocular diseases. All the local ocular diseases of every class of workmen are set forth and from many points of view. But what is of value to the physician and hygienist, profoundly solicitous to prevent the evils, is almost entirely omitted. No ophthalmologists are quoted or referred to who are on record as to the eyestrain origin either of local ocular or general systemic diseases. Poor old out-of-date Halfort (1845) is wholly forgotten. The same diseases are listed as produced by a few diverse callings regardless of the fact that they also exist everywhere and in every occupation. It would appear that to avoid ruination of the eyes by ocular disease all occupations must be given up. All industrial folk, for instance—it would take pages to enumerate the callings—are cursed with nervous, nutritional, and digestional diseases; but the same fatality persists in the majority of others who are not in such occupations. Eyestrain is never alluded to. The real and amazing rôle of presbyopia in every calling or noncalling is forgotten, although in all those working in lead, zinc, quicksilver, gas, and scores of other industries, the limit of industrial capacity is placed at about that terrible eyestrain year, 45. This unexpected and uncomprehended result suggests nothing to the writers. The height of inconsideration is reached in the official tracing of myopia to a multitude of causes but never to the true cause, uncorrected hyperopia, astigmatism, and anisometropia. With dogmatic ruthlessness, myopia is called a disease not at all preventable by glasses correcting the error of refraction—an untruth fraught with tragedy to millions. But swift, safe, or accurate sport or bodily activity, except swimming, is impossible to a high myope. He never dares to run, and all motions must be slow, indefinite and cautious. He walks with a stealthy, catlike step. In long tables the greater incidence of eyestrain diseases according to calling (as in my groups) falls precisely on those doing the greatest amount of near-work with the eyes. Amid all these writings, ever jumps up the hideous Jack-in-the-Box of weird diseases that afflict millions, but which fit into no accepted theory,—"neuritis," and "rheumatism," migraines, headaches, nervous disorders of a hundred kinds, etc.,—the miseries of half the world and the mysteries of the whole.

The wonderful word, "Neurasthenia," for a more mysterious and uncaused disease, increased from 18 percent. in 1897 to 40 percent. in 1904. "No difference as to clinical appearances exists between the neurasthenic workman and the neurasthenic patient of any other social class," is a line of text that suggests, unconsciously, a volume of exegesis. The conclusion is that anemia and neurasthenia are due to "the monotony of work." Not "fatigue," but "monotony" is therefore the stop-gap!

Another study takes up the question of Fatigue in which the conclusion is reached that fatigue itself is the great end and danger of occupation. "The neurasthenics of labor," "the self-generated poisons of disease," "the disturbances of metabolism," are offered as the pathogenic factors. A thousand articles written by reputable and earnest physicians are not even referred to, because they give evidence that the etiology of these enormously increasing neurasthenias and other nervous disorders is clear and prevention possible. The therapeutics offered lead to one and only one measure:—Limitation of the hours of labor. Fatigue as an explanation of occupational diseases obscures instead of elucidating the problem. The difficulty of understanding the causes and of eradicating the evils of such diseases is increased. For fatigue *per se* differs absolutely from disease. What is more profoundly active in producing fatigue of the workman than ignored lateral spinal curvature, present in 83 percent. from adolescence to old age! "Neurasthenia," "Migraine," and a score of other diseases are neither uncaused, incurable, nor unpreventable. They are caused by ametropia, curable, up to about 40 or 45, and always preventable by scientific spectacle lenses.

As to accidental traumatisms, similar misconceptions are met everywhere. Not even the corneal injuries of stonemasons, emerywheel grinders, miners, machine-shop workmen, etc., by "foreign-bodies," are, it seems, preventable. Even simple plano lenses would prevent the wounds and the losses of transparency, and if the ametropic corrections were incorporated many eyestrain diseases would also be obviated. Nowadays the worker with "a foreign body in his eye" is backed against the wall and, with knife or pin, the speck is picked or dug out by some fellow-workman, often with lasting injury greater than if the foreign body were left *in situ*. Obviable, most all of this, if the workman were instructed in the deft use of a simple wisp of absorbent cotton.

Another fact beginning to appear in some of these reports and tabulations is the liability of one eye, usually the left, of course, to be hurt or go out of use. A few Americans, only, have asked, or understood why. The existence of righteyedness or lefteyedness and their relations to righthandedness and lefthandedness will not, alas, be soon recognized.

All the great treatises on industrial diseases do not even allude to the occupations of the majority of the inhabitants,—those of infants learning how to see; of kindergarten children working at near range with fine geometric patterns; of common school pupils; of seminary, college, and university students; of writers and devotees of learning, of farmers, "hands," and peasants; of housewives; of sailors and soldiers; of the leisure classes; of millions in asylums, hospitals, sanitariums, institutions, prisons, etc.; of the senile who do not work; of the unemployed; of craftsmen such as carpenters, masons, builders, etc., in northern climes during winter; of men not laboring during rain,—and many such. Non-occupation may bring on the same diseases or even worse diseases than occupation, especially if near-range vision is forced.

A concrete illustration serves well,—the etiology of myopia. In a country school near Munich the highest class showed that 2.6 percent. were myopic; of the city school the percentage was 9.8; while of those ready to enter the university 55.9 percent. were near-sighted. So far back as 1866 the number of myopes in the University of Breslau was 60 percent.; in 1890 it was 59 percent.; and in 1902 it was 60 percent. If myopia is a non-preventable, causeless, incurable disease, as great and good scientists repeat, then there must be some reason for the statistical differences in our country, since with us the number of myopes is not so great, and we hold a very different opinion concerning the fatalism of the disease. The official examination, by Dr. Dresbach, of 2,484 entering freshmen of Cornell University demonstrated that 87 percent. were hyperopic, while the percentage of myopes was only about eight. And these results, too, were obtained without the use of a cycloplegic. The work of Risley, which fully and clearly showed the etiology and the preventability of myopia has long been before all writers and students, before all who wished to see it and know it. Although writing in 1895 the great English oculist, Simeon Snell, accepts Risley's philosophy of the origin of myopia. No! Myopia does not exist by the will of God or the fiat of fate; it is not, properly speaking, a disease at all; or if so described its origin is known, its preventableness certain. It is caused simply and solely by uncorrected or overcorrected, or by miscorrected hyperopic astigmatism. There need not be a single myope in the civilized world, and there will not be one when the world becomes genuinely civilized.

The effect of pathogenic illumination in factories, workrooms, schools, etc., is a puzzling one to many investigators. They do not know what to do with the question, and the effects, if any do exist, of bad lighting are noted with peculiar vagueness, the recommendations still more vague. But in a recent Massachusetts Report of the State Board of Health it is said that, "It is a well-established fact that either the over-use of the eyes or the use of eyes under bad conditions may give rise to eye-fatigue or to eyestrain; and many eye-specialists believe that at least 80 to 90 percent. of headaches are dependent upon eyestrain. It is impossible to ignore the probability that many individuals working by gaslight, or even by electric light, in dirty, unpainted, overheated rooms, with impure air and excessive moisture, for ten hours a day or merely for the last two hours during the day, use up a great deal of nervous energy, and suffer from eye fatigue or eyestrain, and its consequences."

It is indeed promising that attention to the illumination of factories, etc., is at last being given. But the sober second thought brings the caution that the illumination in the home room of the examiners was, at best, decidedly poor, as they themselves say of so many factories. Omitted entirely are the great governing principles, that the correction of ametropia is the most important of all prerequisites to avoid eyestrain; that poor illumination quadruples all eyestrain; that no tests of measurements whatever of physiologic and of pathogenic illumination are proposed or dreamed of—(as if photometers had never been invented!); that the agencies in creating and doubling poor illumination (never good in any factory in the world) of clouds, dirty windows, rain, fog, by darkness before sunrise and after sunset, wretched artificial lights, and more than all by the smoke-nuisance. These, and many other similar conditions should be emphasized.

It is, in truth, most strange that the science of illumination as related to ocular physiology and pathology has scarcely been thought of. We are in a state of utter barbarism concerning it. With all the writing upon occupational diseases plainly due to under-stimulation, over-stimulation, and morbific stimulation of the eyes by light, the essential and basic principles and sciences of photology and photometry have not even been asked for. The tragedies of the albinos, of the nystagmics, of the glass-blowers, and other cataractous patients, of welders and workers with electricity, of millions of school-children in dark school-rooms, of the snow-blinded,—these show that a new world of truth as to the proper light-stimulus for the eyes remains to be discovered and systematized for humanity's benefit. The use, the non-use, and the misuse, the world over, of burnooses, hoods, turbans, head-wrappings, shades, parasols, fans, hats, caps, etc., are crude attempts to shade the eyes from hurtful illumination. The whole problem of the tropical diseases of the Caucasian, and of Occidental control of tropical civilizations and barbarisms, is not one of heat, but of illumination, coupled of course with eyestrain and the secondary reactions of the organism against light in the pigmentations of the skin, irises, and retinas. The resensitization of the visual purple of the eyes after exhaustion has been such a million-year-long necessity and difficulty that, to insure it, over a dozen distinct physiological ocular mechanisms have been evolved and are active every instant of our waking life.

Atlantic City
N. J.

A Comparison of Photo-electric Cells and the Eye

W. W. Coblentz, Ph. D.

I. Introductory Statement

THIS paper contains a comparative discussion of the photo-sensitivity of the retina of the eye and the photo-electrical properties exhibited by some substances when exposed to light. This may perhaps give us a clue as to how the eye functions when exposed to light. It is also interesting to compare the eye with other instruments for perceiving and measuring thermal radiant energy.

It is so common to hear the expression, "How can you measure the heat in the light of a star?" or "My! Isn't it wonderful that you can measure the temperature of a star"—(which we cannot do)—that, before proceeding with the main theme, it is well to refresh our memories with some of the fundamental facts concerning thermal radiant energy and concerning the instruments used in measuring its intensity.

"Light," "heat-rays," "radiant heat" and "ultra-violet rays" are one and the same, being the vibrations emitted by an incandescent substance such as a tungsten filament lamp, or the sun. They differ only in their frequency of vibration, and wave-length. "Radiant heat" or "infra-red rays" are of longer wave-length than "ultra-violet" radiant energy. There is a continuous increase in wave-lengths, without any gap, from the shortest "ultra-violet," through the "visible spectrum" and thence through the "infra-red spectrum."

This subdivision of the spectrum of thermal radiant energy occurred with the invention of the prism a century or more ago. At that time delicate thermometers were not yet invented and these early experimenters observed that a blackened thermometer, held just behind the red end of the visible spectrum of the sun, indicated the presence of "obscure rays" of "radiant heat" or "heat rays" which warmed the thermometer but did not affect the eye. If they had had the delicate instruments of today, which can detect and indicate a rise in temperature of 1/1,000,000 degree, they would have found "heat" (a heating effect) produced by the "light" of the sun. It is simply a question of sensitivity of the instrument and, as will be noticed presently, no single instrument has yet been developed which compares with the retina of the eye in sensitivity to thermal radiation.

On the other hand, beyond the violet end of the visible spectrum these early experimenters found that an effect was produced upon a photographic plate; and they called this part of the spectrum "actinic rays."

While these subdivisions still remain true in part, modern experimenters, by sensitizing their photographic plates, are now able to obtain "actinic effects" throughout the ultra-violet, visible, and even into the infra-red, to wave-lengths of about 0.001 mm. Moreover, by means of very delicate radiometers, they are now able to measure the thermal value of the ultra-violet as well as the visible and infra-red rays.

Hence, as already stated, as determined by their heating effect, there is no real gap or difference between these three subdivisions of the spectrum. The thermal quality of these rays is essentially the same; though their (intensity) energy value or "mechanical equivalent" differs greatly, depending upon the source of radiation, *e.g.*, the sun, a carbon arc lamp, or steam radiator.

However, we are learning new things every day and must not be hasty in casting aside these convenient classifications or subdivisions of the spectrum. In comparison with the infra-red rays, the ultra-violet rays are able to produce an "actinic" or photo-chemical effect far greater than would be expected from a measurement of their thermal ("heating") value, as measured in gram calories or ergs. Ultraviolet rays coagulate albumen very rapidly, which is not true of infra-red rays of equal thermal value. Looking at a quartz mercury vapor lamp, or the iron arc, for only a few seconds may cause permanent injury to the eyesight. The action is photo-chemical. The living cells are injured. One would have to "cook" the eye quite a while with infrared rays to produce a similar condition. If we consider the process in terms of thermal units of energy expended, the coagulation of albumen in hard-boiling an egg is quite a different proposition from a similar process by means of ultraviolet rays.

There seems to be considerable misconception concerning the functioning of selective and non-selective radiometers. Hence, before discussing the eye and the photo-electric cell, it is relevant to add a few comments on the physical conditions which control the selectivity and non-selectivity, also the proportionality of the response, when the radiometer is exposed to radiant energy of different wave-lengths.

A radiometer, giving responses which are directly proportional to the incident radiation, is not necessarily equally sensitive to all wave-lengths. The thermopile is a typical example. The surface of the receiver is equally sensitive to all wave-lengths because it is covered with lampblack, which has the property of absorbing equally (within experimental errors of observation) all wave-lengths. If the thermopile receiver were covered with aluminum oxide*, it would absorb only 15 percent. in the visible spectrum, while at 8.8μ in the infra-red it would be as "black" as lampblack, absorbing 98 percent. of the incident radiation. Evidently the question of equality of sensitivity for different wavelengths depends entirely on the kind of material used as an absorbing surface of the thermopile (or bolometer) receiver.

Bureau of Standards, Vol. 9, p. 293, 1913.

The response of the thermopile is directly proportional to the intensity of the incident radiation because, for the small rise in temperature involved, the thermal e. m. f. generated is directly proportional to the heat generated, which in turn is directly proportional to the energy absorbed. However, in order to utilize this direct proportionality of response of the thermocouple it is necessary to design the galvanometer so that its deflection is directly proportional to the current passing through the circuit.

On the other hand, the distinguishing characteristic of the photo-electric cell is its selective sensitivity or response to various wave-lengths, being the most sensitive to the ultra-violet. Thus far it has not been possible to modify appreciably this inequality of sensitivity for different parts of the spectrum. However, while most photo-electric cells do not give responses which are directly proportional to the intensity of the incident radiation, it is possible to design the cell so that it gives direct proportionality of response.

In concluding this part of the discussion, it is relevant to add that the eye is one of the most sensitive detectors of radiant energy. The unaided eye can detect a seventh to eighth magnitude star. It requires a 3-foot reflecting telescope to detect a seventh-magnitude star by means of its total radiation. On the basis of the "light" emitted from a star, assuming a luminous efficiency of 20 percent., it would require a 7-foot telescope combined with a stellar thermocouple in order to attain the sensitivity of the human eye! Calculations show that the eye responds to light having an intensity less than 1×10^{-9} erg,—a value so small that it would require sixty million years to raise 1 g. of water 1° C. Since the thermocouple (or bolometer) is non-selective, it gives an accurate register of the radiation from an incandescent body; as, for example, a star. The stars that appear the brightest to the eye do not necessarily appear the "brightest" radiometrically, because they may have dark companions which emit considerable infra-red radiation.

Readers interested in a more detailed discussion of instruments and methods of radiometry are referred to more complete papers on this subject.*

II. The Human Eye as a Radiometer

From the foregoing discussion it is evident that the eye, unlike a thermopile, or a blackened thermometer bulb (which responds equally to all frequencies of equal energy value) is "selective" in that it is sensitive to only a limited range of frequencies of radiant energy, called the "visible spectrum."

It is therefore of interest to summarize what is known concerning the response of the eye for different intensities and for different colors of the exciting light.

In these tests the energy value of the various light stimuli is made equal by means of a non-selective radiometer, *e.g.*, a thermopile. The eye is then exposed to these light stimuli and the effect noted. The result is illustrated diagrammatically in Fig. 1, in which curve *A* gives the responses for a low intensity and curve *B* represents the responses for a high intensity. These are the so-called visibility of radiation curves for an equal energy spectrum.

The first thing to be noticed is that the physiological response, whatever that may be, is a maximum in the yellow-green and drops off very rapidly in the red and in the blue. For high intensities the curve *B* is shifted toward the red,—the Purkinje phenomenon.

These responses differ for different persons, some of whom are especially sensitive in the blue, green or red. The composite‡ curve of 125 observers is illustrated in Fig. 2. It is a striking example of the great variability which occurs in the visibility of radiation of the human eye. Persons who are partially color blind, *i.e.*, confuse colors, have a distorted visibility of radiation curve, Fig. 3. The visibility of radiation curve of a totally color-blind person is shifted to the blue, as shown in Fig. 4.

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*Bur. Stds. Sci. Papers, Nos. 85, 188, 196, 229, 261, 282, and 319.

‡Bur. Stds. Sci. Paper, No. 303.

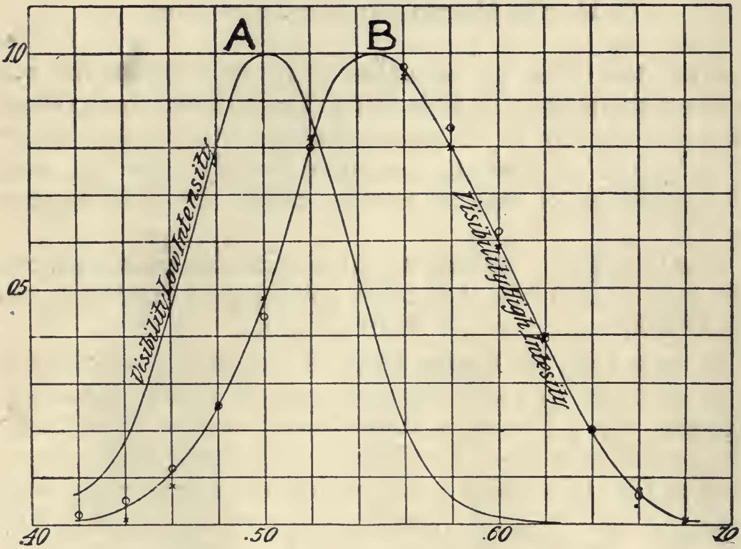

Figure 1. Relative Sensibility of the Eye to Light of Different Colors or Wave-lengths.

In comparison with other radiometers it is of interest to note the speed with which the response occurs for different wave-lengths of light. When the eye is suddenly exposed to light of different colors, it is found that the growth of visual sensation* with time is much more rapid for blue light than for red light. Fatigue sets in and, after passing through a maximum, the visual sensation decreases somewhat in value. For low intensities, it requires a long time for the visual impression to attain its maximum value. For ordinary intensities the full sensation is attained in a few hundredths of

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*See Nutting's Outlines of Applied Optics, Fig. 40.

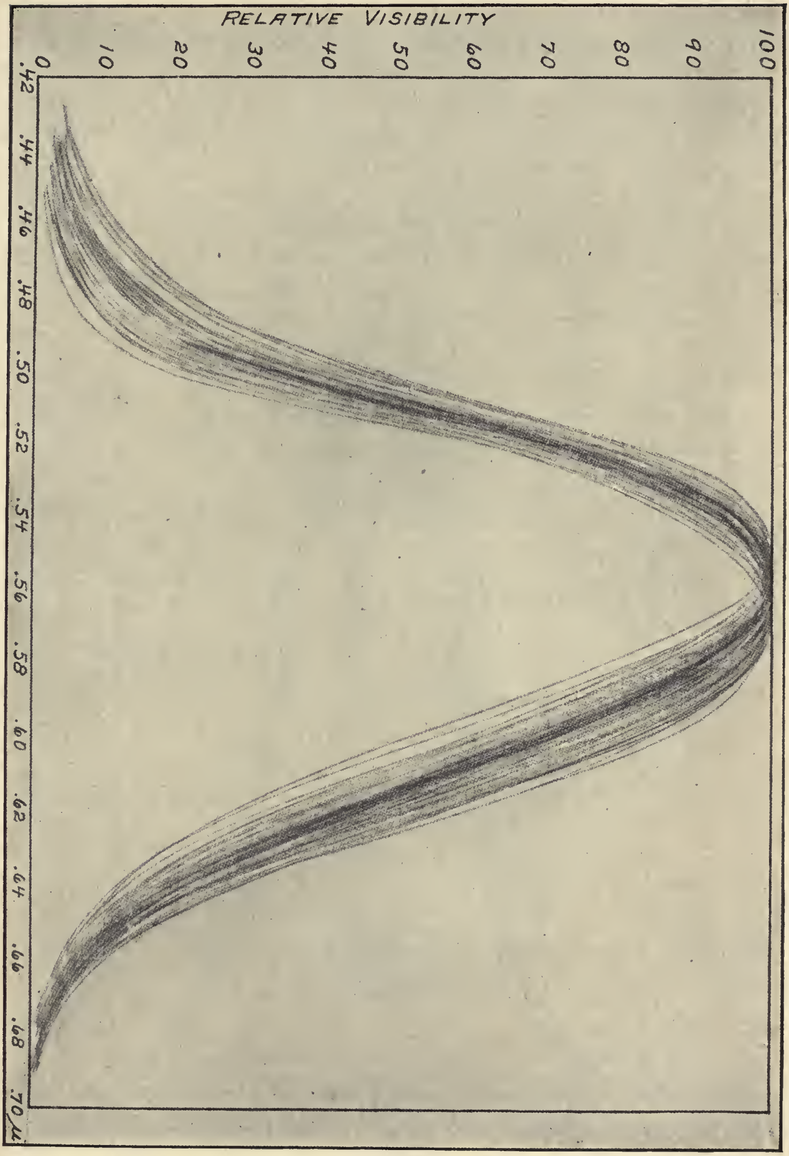

Figure 2. Composite Sensibility Curve of 125 Observers.

a second as compared with a photo-electric response in a solid conductor, *e.g.*, selenium, which requires several minutes. In the eye, the response-time and the recovery-time intervals are practically the same. In the case of photo-electric substances (solids) the recovery-time may be several times longer than the response-time. The response of the eye to light stimuli is so complicated in comparison with that which is observed in photo-electric substances that it seems futile to elaborate the comparisons.

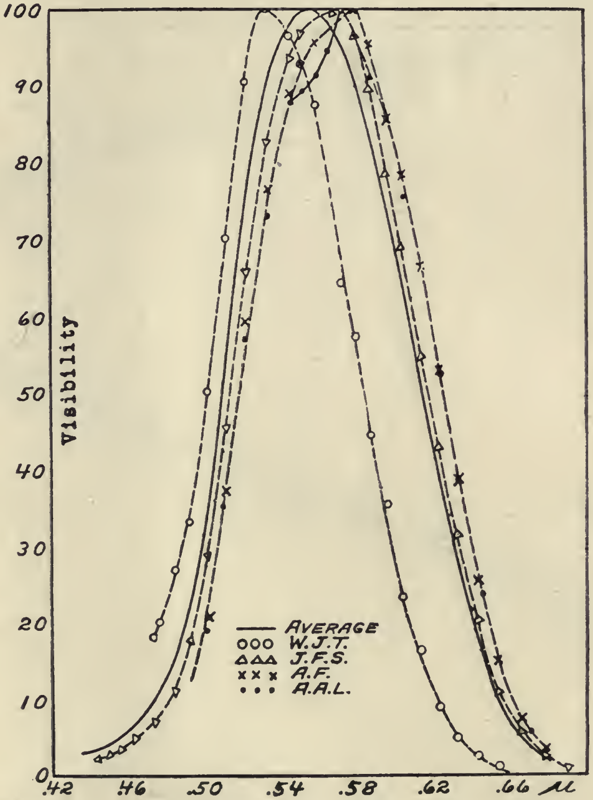

Figure 3. Sensibility Curves of Color-blind Subjects.

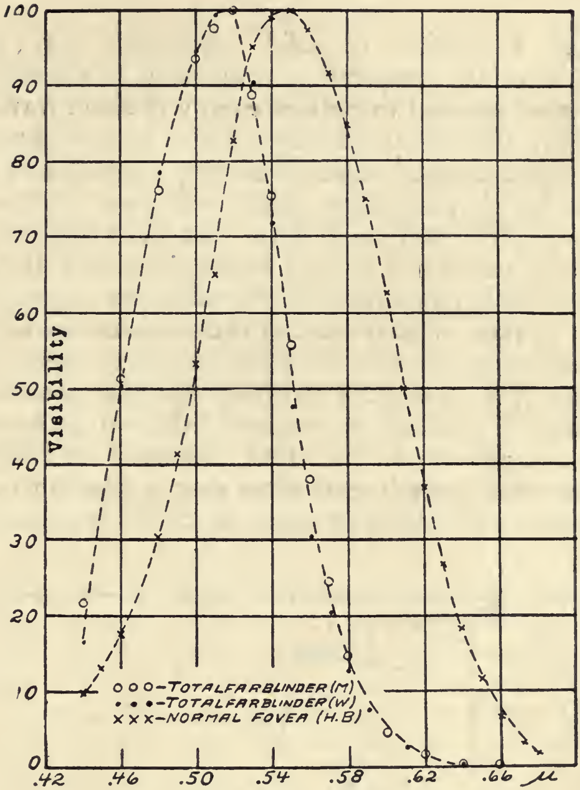

Figure 4. Sensibility of Color-blind Eye to Equal Spectral Energy Stimuli.

To conclude, it will suffice to say that the eye cannot be used as a radiometer to measure directly the intensity of radiation. It can equate the intensities of two lights of the same color, and it can make some rough guesses of the equality in intensity of two sources of light differing in color; but that is all.

III. The Photo-electric Cell as a Radiometer

It is necessary to distinguish between two kinds of photo-electric substances.

Group I consists of solid conductors, *e.g.*, selenium, which have the property of decreasing in electrical resistance when exposed to radiant energy of short wave-lengths, especially the visible and ultra-violet rays. The character of this phenomenon depends entirely upon the wave-length (frequency) of the radiant energy stimulus. It does not depend upon thermal conditions; that is, it does not depend upon the amount of radiant energy absorbed and the consequent rise in temperature of the substance exposed to radiation. In fact, at least some of these substances undergo the greatest change in resistance (are the most sensitive) for radiations of wave-lengths which are the least absorbed. The resistance of selenium increases with decrease in temperature, which is opposite to the effect produced by "light" rays. For example, experiments show that a selenium cell having a resistance of 1,000,000 ohms at 20° C increases to three times that value (3,000,000 ohms) at 0° C. When such a cell is exposed to diffuse daylight, its resistance decreases to one-tenth to one-fiftieth of its value when unexposed to light,

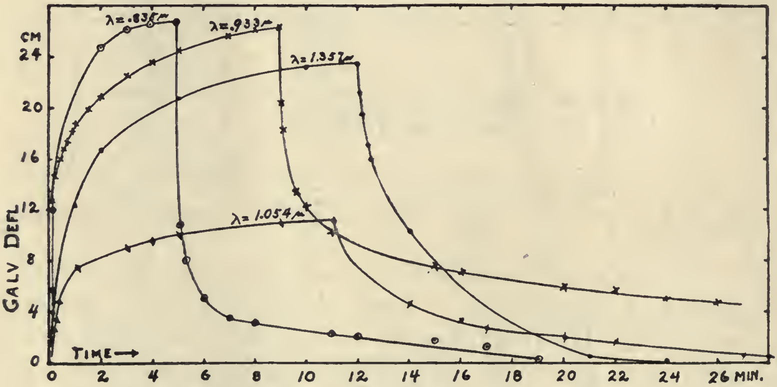

Figure 5. Variation of Photo-electric Current in Molybdenite with Time of Exposure.

in spite of the fact that the temperature rise is perhaps only 1/100,000 of a degree.

Like the eye, these photo-electric substances are selective in their response to thermal radiation. Moreover, in selenium there is a lag in the rate of the response-time curve (and in the recovery-time curves), which is not unlike the growth of visual sensation of the eye. The position of the maximum sensitivity curve, with increase in intensity of the energy stimulus, shifts somewhat toward the long wave-lengths. Moreover, in solids, the response-time curve, Fig. 5, appears to be greater for the long infra-red rays than for the visual rays.* Having these observations upon only one substance, selenium, it was perhaps but natural for some philosophers to see analogies in the photo-electric cell and the eye.

However, in a recent investigation† it was found that, for the visible spectrum, up to wave-length 0.647μ, the photo-electric response in molybdenite is positive or negative depending upon the voltage applied to the terminals of the cell. For a high voltage, the response (galvanometer deflection) was negative, and the time required to reach a maximum response was as great as for the long waves. These observations completely upset our preconceived notions, and raise the question whether, under proper conditions, the response-time in selenium is different for the different wave-lengths used as stimuli. At least, it is questionable whether we can compare the selectivity as to the wave-length of the rate of response with time of a photo-electric substance with that which obtains in the eye. The analogy seems far-fetched.

Group II includes substances which, when charged to a negative potential (in an evacuated chamber), lose their charge when exposed to light, especially violet and ultra-violet rays. When used in this manner they are commonly called

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*Bur. Stds. Sci. Paper No. 338.

†Colbentz & Kahler, Jour. Wash. Acad. Sci., 9, p. 537; 1919.

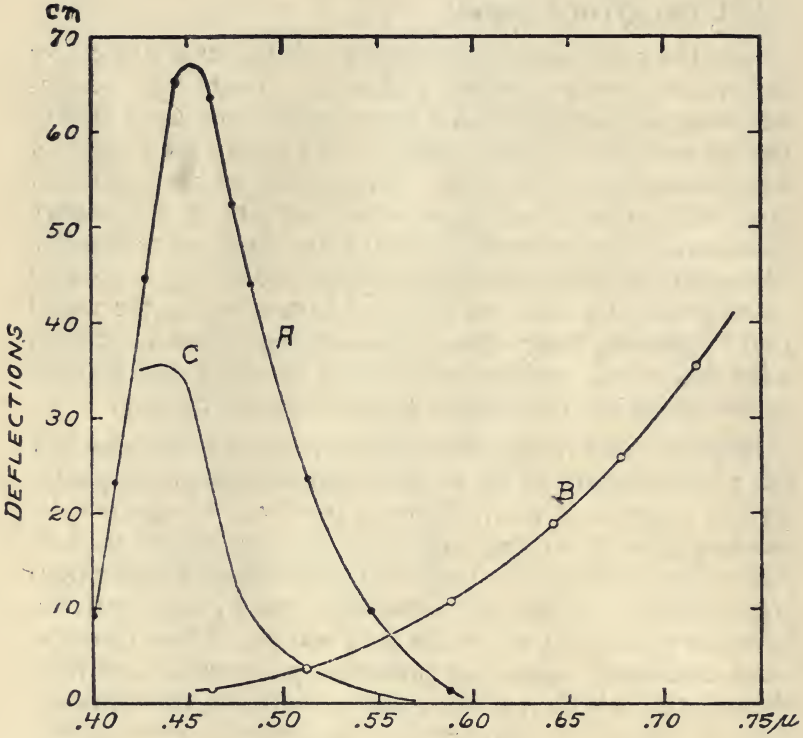

Figure 6. Distribution of Energy of a Gas-filled Tungsten Lamp as observed with: A, photo-electric cell; and B, with a thermopile. Curve C is the true sensitivity of the photo-electric cell for an equal energy spectrum.

"photo-electric cells." The emission of electrons is a surface phenomenon which is easily affected by oxidation of the surface.

From some reports it appears that the effect produced by exposing the electrode to light does not disappear instantaneously. There is no great delay, however, in attaining a maximum response on exposure to light, as obtains in solid conductors, *e.g.*, selenium. This type of photo-electric phenomenon is selective* to wave-length, as shown in Fig. 6, which gives the spectral energy curve as observed with a photo-electric cell, *A*, and a thermopile, *B*. But, thus far, no selectivity (lack of proportionality) of the response as dependent upon the wave-length of the exciting light, has yet been reported. In this respect the gas-ionic photo-electric cell differs from the eye, and perhaps from solids exhibiting photo-electric sensitivity.

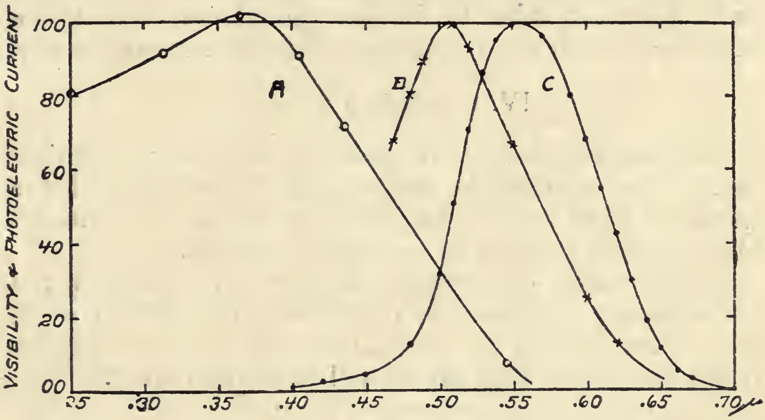

Figure 7. Photo-electric Sensitivity: A = Calcium; B = Rubidium; C = Sensibility of the Average Eye.

The sensitivity curves, for light (radiation) stimuli of equal energy value, as observed in photo-electric cells of calcium, *A*, and rubidium, *B*, are given in Fig. 7. Curve *C*, Fig. 7, gives the visibility of radiation of the average eye. It will be noticed that there is no marked similarity between these response curves. Indeed, a characteristic of the gas-ionic photo-electric cell is its high sensitivity to violet radiations, where the eye has a low sensibility. There is, therefore, no similarity in the results obtained by comparing the response of the eye with that of the photo-electric cell; and it is not apparent that there is any similarity in the functioning of the retina and these photo-electric substances.

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*Bur. Stds. Sci. Paper No. 319.

Furthermore, in view of the great dissimilarity in the response curves of these two instruments, the gas-ionic photo-electric cell cannot be substituted for the eye in practical photometry. The selenium cell, with its selective sensitivity to intensity as well as to wave-length, is even less adaptable to photometry. Nevertheless, we see the inventor rushing off to the patent office with useless applications, which may flatter his vanity when he sits in contemplation of his devices but which do not add to the store of useful accomplishments.

IV. Concluding Remarks

The task before me is to assemble the evidence, pro and con, to see whether the functioning of the eye, in its response to light stimuli, has anything in common with the photo-electric response in inanimate material.

In this paper observations are presented showing that when the eye is exposed to stimuli of radiant energy of different wave-lengths, but of equal thermal value, the response is selective to the intensity as well as the wave-length of the exciting radiation; or in the more popular phrase, it is selective to light of different colors and intensities. Moreover, the rate of response is selective as to wave-length, and when the response has attained a steady state, the maximum of the visibility of radiation or sensibility curve is found in the yellow-green of the "visible" spectrum.

On the other hand, the photo-electric response depends upon the manner of applying the stimulus. In the gas-ionic photo-electric cell, the response of the negative electrode, when exposed to light, is vaguely analogous to the retina of the eye. But the spectro-photo-electric response or sensitivity curve has its maximum, if any, in the extreme violet, where the eye is quite insensitive to radiation; and the shape of this sensitivity curve is only very vaguely similar to the sensibility curve of the eye. Moreover, the gas-ionic photo-electric response is not selective to intensity; neither is the rate of response known to be selective as observed in the eye. The possible "after-effect," similar to the persistence of vision, which occurs after exposure, needs further and very careful investigation to make certain that there is such an effect.

Turning now to the spectro-photo-electric sensitivity in solids, we find that, like the eye, they are selective as to wave-length and intensity. But the maximum response to radiation stimuli occurs usually in the extreme red* or even far out into the infra-red and there is no similarity to the visibility of radiation curve of the eye.

Recent experiments have shown that, in some cases at least, the photo-electric response in molybdenite is positive or negative, in the visible spectrum, depending upon the voltage applied; also that the rate of response to the radiation stimulus is selective or non-selective depending upon the voltage applied.

Considered as a whole, the phenomenon of spectro-photo-electric sensitivity in solids is only vaguely, if at all, similar to the visual response.

Combining the gas-ionic, spectro-photo-electric response with that observed in solids does not give us a composite effect which is analogous to the selectivity of the eye (1) to the rate of response, or (2) to the intensity, and (3) to the wave-length of the exciting light. Neither does persistence of vision, color of after-images, etc., which obtain in the eye, have a counterpart in photo-electric sensitivity.

In the writer's opinion, evidence is not sufficient to conclude that there is a connection between the phenomena of color perception and brightness perception, and the phenomena of photo-electric sensitivity of inanimate material.

Washington,
D. C.

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*Bur. Stds. Sci. Paper No. 338.

The Value and Limitations of Perimetric Methods of Study

Luther C. Peter, M. D.

TO obtain the best results in perimetric studies, the limitations as well as the advantages of the methods employed must be thoroughly appreciated. To the careful observer, three definite conclusions are justified by experience, namely: 1. Each of the approved methods of study has problems for the solution of which it is especially adapted. 2. Each one has peculiar and special limitations. 3. No one of the methods is applicable or equally adapted to all studies required in perimetry. If we, therefore, approach this discussion with these three well established facts in mind, the relative value and the limitations of each method can be determined without bias and with a fair degree of scientific accuracy.

For purposes of study four distinct methods should receive consideration, namely: first, the hand method; second, studies on the perimeter; third, the campimeter; fourth, stereoscopic measurements. In the first or hand method the operator uses his own field as a standard to check up marked defects in the visual field. In routine office practice when marked cutting in the fields is evident, particularly in the form of the anopsias or in marked consensual contraction, the method offers a ready means of satisfying the observer that careful perimetric studies should be made. In children and in the insane, its modifications may be employed to advantage. In class work and for bedside studies it also has a field of application. All agree, however, that it is but a method of detecting gross limitations of fields and should be followed by one of the more accurate methods of study. Its application consumes so little time that there can be no excuse for the omission of the study when gross changes are suspected or indicated by the patient's history or symptomatology. No one, however, would attempt to lay other stress upon the findings than that they point the way to a more careful investigation of the case.

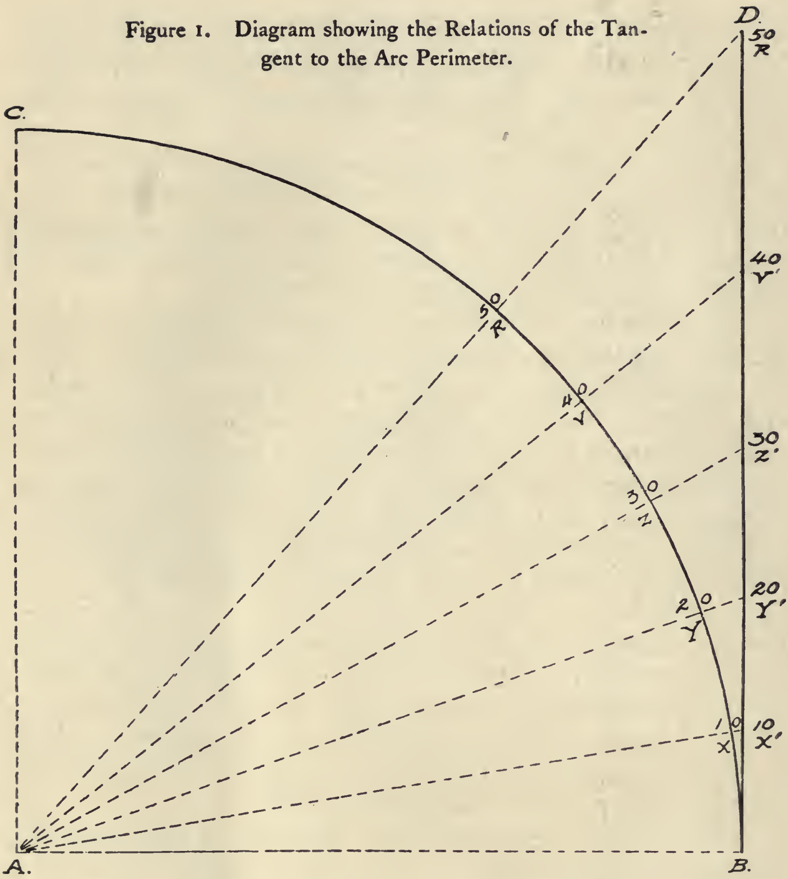
In order to appreciate the advantages and limitations of the perimeter and campimeter, two considerations must receive our attention; first, what particular changes are sought in perimetric studies and, second, what are the principles of construction of the perimeter and campimeter.

The character of the changes sought naturally are of the greatest importance. In normal fields but two things are to be determined; first, the outline or silhouette of the field, and, second, Mariotte's blind spot. In disease, however, to the silhouette or peripheral limitations are added the more important studies of central and paracentral field defects, enlarged blind spot of Mariotte and particularly qualitative color changes which ofttimes are the earliest signs of disease. As the retina is poorly supplied with rods and cones in the periphery and becomes increasingly rich in these receptive end organs as the fovea centralis is approached, it at once becomes apparent that changes in the central zone are really the changes which require our most careful consideration. In other words, peripheral field changes are neither so vital to the patient nor so helpful to the surgeon in diagnosis as are the changes found in the central zone.

In the normal case the average 5 mm. disc of white may be recognized temporally up to about 85°, nasally about 40°, above about 40° and downward as low as 70°. Pathologic changes of any moment will, therefore, fall within the 40° circle around the point of fixation, and it is this particular area which needs the most careful scrutiny. The method, therefore, which lends itself best to the study of the changes which fall within the 40° circle is the one which should be adapted.

In the examination of the principles of construction of the perimeter and campimeter, the reader is referred to Fig. 1.

Figure 1. Diagram showing the Relations of the Tangent to the Arc Perimeter.



The curved line C-B represents the arc of the perimeter, and D-B the tangent to the same or the campimeter. It becomes self evident that the radii of the arc and the distances from the eye to the tangent surface are almost the same up to the 20°. On the perimeter each ten degree interval is equally distant from the succeeding interval which is a multiple of ten. On the campimeter this is not true, for the intervals gradually widen. Up to 40° this discrepancy is not of sufficient moment to interfere with practical work and up to 20°—like the centrad and diopter units of prisms—the difference is inappreciable. It is safe to say, therefore, that the campimeter is accurate up to 20°; from 20° to 40° it becomes increasingly inaccurate and beyond 40° practically unsatisfactory.

Let us see, therefore, how this applies in working out a normal form and color field. Above, the form field rarely exceeds 40°. To the nasal side this is equally true. Downward the normal field may reach to 65° or 70° (as a matter of fact, however, it rarely does). To the temporal side it should extend to 85°. For form, therefore, normal limitations may be measured on the campimeter above, in and approximately down, while the temporal field will be inaccurate.

As the blue field falls approximately 10° inside the form field the same may be said of measurements of this color. Normal red and green, however, may be measured on the campimeter with as much accuracy as on the perimeter. Central normal fields, therefore, may be studied on the campimeter as well as on the perimeter.

How does this apply to pathological changes? As peripheral retinal disease causes a gradual contraction of the form as well as of the color fields, pathologic fields in most instances may be outlined on the campimeter even though normal form fields do not admit of accurate measurement on this instrument.

The more important studies in perimetry, however, are confined within the central areas, and it is in this particular phase of perimetry that the campimeter especially excels. Its flexibility in studying the normal blind spot and central changes can be appreciated only by one who has tried both methods. A study of the blind spot of Mariotte on the perimeter is almost an impracticability to even the most expert. On the campimeter and especially on the hand campimeter which bears my name, the normal blind spot is worked out with the utmost ease, and it is an admirable way to begin

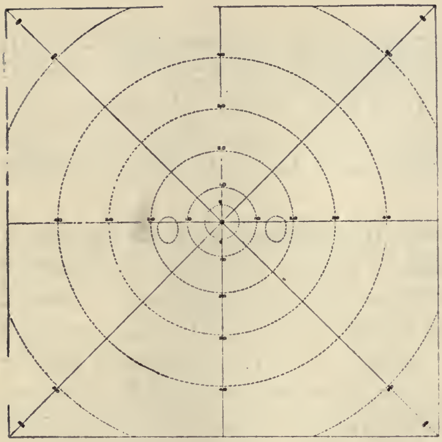


Figure 2. Peter's Record Chart.

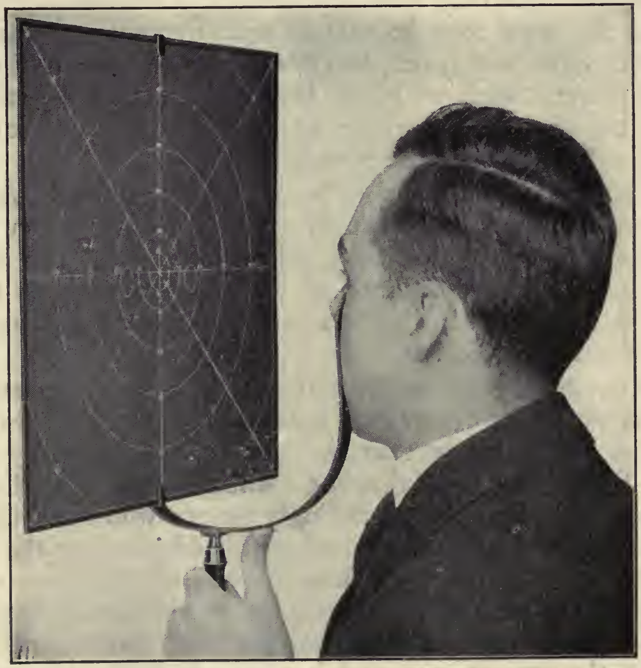


Figure 3. Peter's Hand Campimeter.

the "taking of a field" because the patient is quickly trained to steadfastly gaze upon the fixation spot. Only by concentration can the blind spot be properly outlined and the training which the patient receives in this guarantees more accurate and correct measurement of the form and color fields.

That which is true in determining the outlines of the normal blind spot applies with equal force to any change which may take place in the central field. All of these studies are simplified, results are more accurate, and the "taking of a field" is accomplished more rapidly than when the more cumbersome and inelastic perimeter is employed.

Other elements operate to the disadvantage of the perimeter. It is an instrument of considerable size and weight and cannot always be placed in a good light, which is a *sine qua non* of "field taking." Automatic perimeters, which are now employed, carry the small test object on a carriage of considerable size, which, in addition to the noise it makes, is disconcerting to the patient, as its movements are noticeable and may cause inaccurate results. Test objects on the campimeter of the knife edge variety, as described by Walker, of Boston, and others are attached to slender black rods which are inconspicuous. These are moved about noiselessly and flexibly over the campimeter surface, and are unobtrusive and inconspicuous. In a scientific laboratory tangent screen, which has lately been devised, the test objects consist of small spheres of metal which are controlled by a magnet from behind the screen so that only the test object of a definite size is seen by the patient. This is an ideally accurate campimeter for laboratory purposes but does not lend itself well to general adoption in routine office practice.

Other modifications of the tangent screen for the practicing of the Bjerrum method have special advantages for definite phases of study and likewise their disadvantages. Their disadvantages lie largely in their size and the difficulty encountered in illuminating the surface. The latter element can be overcome but it increases the bulk of the instrument. Their special advantages lie in the adaptability to the taking of a tubular field and in enlarging small scotomata by moving the patient further from the screen. The so-called Bjerrum screen of large size, of which Duane's tangent screen is a good type, therefore, becomes largely a hospital or a laboratory instrument and not well adapted to office use.

On the relative merits of the perimeter and campimeter, experience justifies the following conclusions:

1. The chief and practically the only advantage of the perimeter is in the taking of normal or nearly normal form and color fields.*
2. The campimeter is ideally adapted to studies within 30° of the fixation point including especially the blind spot of Mariotte and the study of central and paracentral scotomata.
3. Inasmuch as most field studies are made on pathologic cases and a fair degree of accuracy can be obtained in peripheral delimitations up to 40°, the campimeter may and should be used for the taking of peripheral fields when the form fields are approximately within the compass of the campimeter.
4. The campimeter reduces the time of taking fields.
5. The campimeter because of its elasticity, its accuracy and its adaptability to the essentials of "field taking" is the instrument of the writer's choice.

The study of central scotomata by means of the stereoscope and Haitz charts has opened up the way to a much better as well as an enlarged field of investigation. These methods have been improved upon by Bissell, of Rochester, who has enlarged the field of study to include the blind spot of Mariotte. And, again, quite recently a stereo-campimeter slate has been devised by Lloyd. This slate is an addition of considerable merit to our methods of central field

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*The writer does not wish to exclude the special adaptability of the perimeter to the measuring of the angle of squint and in determining ocular rotations for which it is ideally adapted. These phases of its use, however, do not fall within the domain of perimetry.

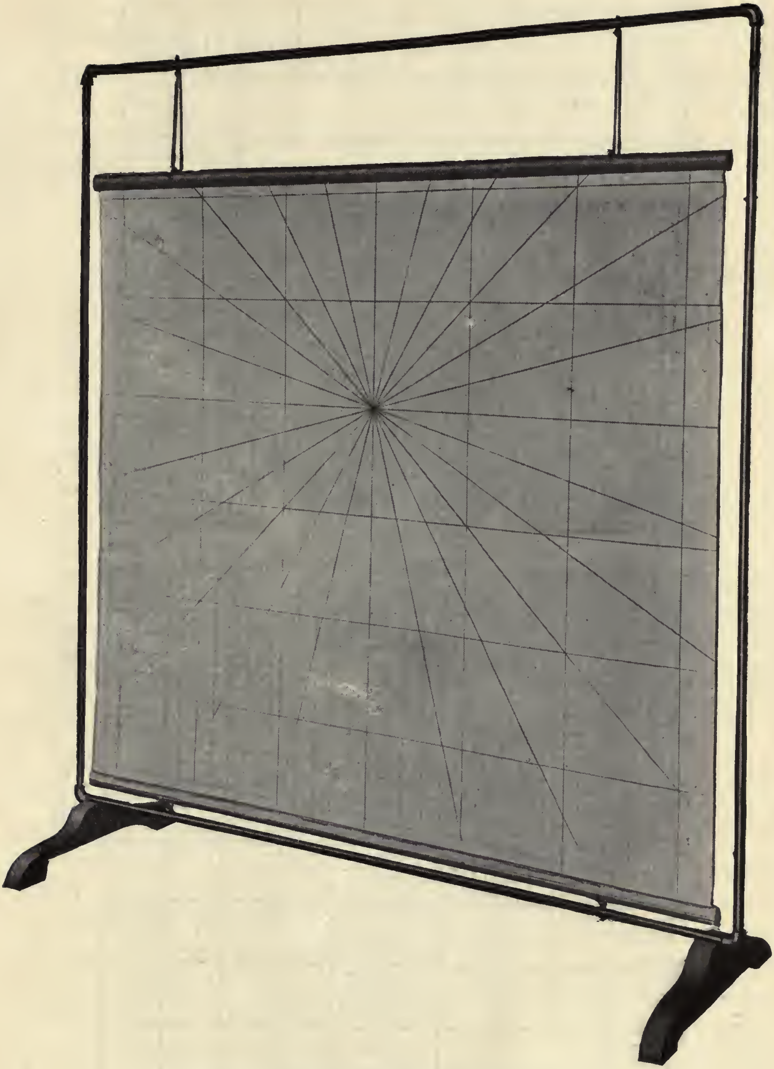

Figure 4. Duane's Tangent Campimeter.

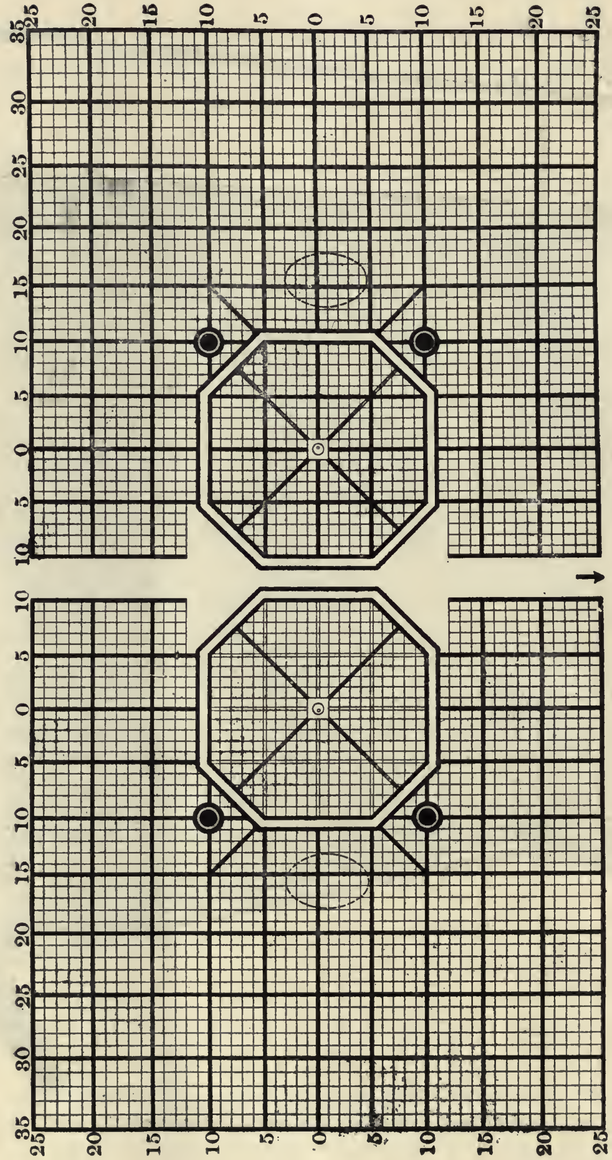

Figure 5. Lloyd's Record Chart for Stereo-Campimetry.

study, for it admits of a minute examination of a caeco-central area, extending nasally about 12°, upward about 25°, downward about 12° and temporally about 25° or possibly 30°. The actual slate is marked to include a larger area but the field of study is limited by the frame work of the stereoscope to the actual measurements given above.

Advantages:

1. For a study of the blind spot of Mariotte it is ideally adapted and by it a more accurate outline of the blind spot may be obtained than on the hand campimeter.
2. In unilateral scotoma involving central fixation and included within the limits above given, it furnishes probably the most satisfactory method of study. It, of course, is limited to these phases of study and in its *restricted* field is not excelled or perhaps equalled by any other method.

In a caeco-central scotoma extending beyond its cope it cannot be used and recourse must be had to the hand campimeter or some other form of tangent screen. When both eyes are the seat of central scotomata it is impracticable and the hand campimeter or tangent screen must be resorted to by methods to be discussed in a subsequent paper.

It is an interesting but not an entirely satisfactory commentary on the chapter on Perimetry to note with what tenacity men cling to an instrument so inadequately adapted to its task as the perimeter. Constructed originally to delimit the most peripheral field, normal and pathologic—a function for which it is well suited—it is still employed for the study of what we now know to be the more important phases of field changes, namely, an examination or analysis of *central defects*. That the various types of the campimeter are better adapted for this part of the work is freely admitted by all who are familiar with the technique; but in practice, if the literature is a fair index of the methods employed, it is not the rule. Furthermore, the fact that the campimeter is well adapted to pathologic peripheral study does not receive proper recognition.

I am not prepared to consign the perimeter to the scrap heap nor do I regard the instrument as entirely obsolete. The positions, however, of the two types of instruments, in so far as their relative value and practicality are concerned, should be reversed. The campimeter should be the instrument of choice and the perimeter should be reserved for the few studies for which the campimeter is found to be inadequate.

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Abstracts and Reviews

A Test for the Judgment of Distance

Capt. Harvey J. Howard, M. D., Oph. D.

(From the Research Laboratory, Mineola, N. Y. Original paper published by permission of the Board of Publication, S. G. O.)

AVIATION during the past few years has brought up the practical problem of the judgment of distance. Tests for stereoscopic vision, so called, made by the hand stereoscope have been found satisfactory for extremely rough distinctions in such tests. For the subject tested will either project all the stereoscopic pictures fairly accurately or else get no projection at all.

Judgment of distance is dependent upon several factors, some of which are monocular and others binocular. The factors common to both binocular and monocular vision in the matter of judging distances are: (1) Size of retinal image, (2) accommodation, (3) motion parallax, (4) terrestrial association, such as linear perspective, overlapping of contours and light reflections and shadows or shades, and (5) aërial prospective. Factors operative in binocular single vision only are: (1) Binocular parallax and (2) convergence. In this important research in physiological optics Howard has eliminated, for good and sufficient reasons, all factors but binocular parallax and the size of the retinal images. The relative importance of these two factors can be determined by the use of the same test apparatus using, first, both eyes and then one eye only. The size of the retinal image is as important a factor with one eye as with two. But if investigations should demonstrate that the binocular test is the more sensitive in discrimination, then the size of the retinal image would be a secondary consideration or factor. Howard very properly points out that, all other factors than these two—with the exception of accommodation and convergence—are extraneous to the individual and do not represent that difference in ability characteristic of him.

Howard used as a testing device a modification of an apparatus devised by James of England in 1908 (*Lancet*, page 1763, 1908). A suitable box is provided, carrying an opening in the front and a board fastened to the bottom of the box and drilled with suitable holes for carrying the test rods. In making a test the person is seated six meters away and the observer's eyes are arranged to be at the same height as the middle of the window. A screen covers the window and when the test is to be made the observer is told to fix a point near the center of the screen. The test rods being in position, the screen is suddenly raised and the observer is asked to state which of the rods is nearer to him. As a rule the first observations were made with a 30 mm. depth difference, *i.e.*, when one rod is in a reference plane 6000 mm. away and the other is 6030 mm. away. If a set of twenty judgments is correct, tests are made at the 20 mm., the 15 mm., and so on, stations until it is apparent that "guessing" is the only thing involved. The binocular parallactic angle is represented linearly by the depth distance and simple trigonometrical relations enable this angle to be calculated. A moment's consideration shows that this must vary with the observer's interpupillary distance.

Howard set as his standard, not the shortest depth distance at which 100 percent. correct replies were made but rather the shortest distance at which he was still within his threshold. He accepted as the threshold that least depth distance at which the judgments were correct not less than 75 percent. of the time.

Captain Howard discusses at great length his findings on about 100 observers, and gives complete tables of all his data. The factors of visual acuity, muscle balance, accommodative amplitude and convergence power are discussed and their bearing upon the problem in hand made clear. In a general or rough way the data show that errors of refraction, muscular imbalances and allied physiological factors cause a decrease in the ability to accurately judge distance.

In the paper it is pointed out that "To determine what should be called a 'normal' or 'not normal' in the judgment of distance is a very difficult proposition. It is decidedly a relative matter especially when an examination affords a classification as this one does. A careful study of the data, however, convinces me that a break occurs between the 20 and 30 mm. depth-differences. Beyond the 20 mm. station there seems to be a physical cause for a poor showing in almost every case. With some it was visual asymmetry or some muscle imbalance. With others there was a persistent tendency to project one image nearer. Or it may be that the subject was wearing a high correction.* * * Therefore, basing my conclusions upon all the facts at my disposal I feel justified in recommending as normal a binocular parallactic angle not greater than 8.0 seconds when the test is made with an apparatus made on the principles of the one used in these experiments. An important feature of the test is the use of the screen or shutter. Lifting this quickly gives a sudden impression of the rods which is more accurate than is a delayed impression. In fact most of our everyday depth judgments are made instantaneously or practically so."

Tests were made to determine the ability to judge which of the two rods was nearer when the apparatus was turned over on its side, hence putting the rods in a horizontal position. In this case the advantage of binocular parallax is eliminated and the judgment of the relative positions of the horizontal rods was no better with both eyes than with either one, and was reduced to the one factor, namely, size of image.

The conclusions on the matter of our judgment of distances are:

1. Of all the personal factors which aid us in the judgment of distance, the binocular parallax is the most import-

ant. By experiment it was found to possess twenty times the ability of the retinal image or visual angle which is the important factor in monocular judgment. This, however, should not represent the comparative depth judgment skill of two and one-eyed persons, because in actual life the extraneous factors, by helping both equally, serve greatly to lessen the difference in ability of the respective personal factors.

2. The minimal binocular parallactic angle varies greatly with individuals. It depends upon such factors as visual acuity, equality of visual acuity or visual balance, muscle balance, interpupillary distance and probably some innate and acquired ability.

3. Judgment of distance to a remarkable degree exists when the parallactic angle (binocular) ranges in the neighborhood of two seconds.

4. To possess normal judgment of distance one's binocular parallactic angle should not be greater than eight seconds when the test is made with an apparatus constructed on the principles employed in the foregoing investigation.

5. The apparatus used is free from the criticism applicable to the hand stereoscope and also admits of the classification of individuals according to their discriminating ability.

6. The value of such an apparatus is greatly enhanced and much smaller discriminations are possible by giving the observer a sudden impression of the objects to be judged. Otherwise a disconcerting fluctuation of objects arises.

7. The binocular parallax operates in the judgment of objects maintaining some horizontal or lateral separation, but not for superimposed objects like telegraph wires. In this latter instance the judgment is dependent upon the interpretation of the retinal images when all factors extraneous to the individual like terrestrial association and aërial perspective are excluded.

8. Direction and distance must be known to correctly locate an object. Direction is judged more accurately with one eye but distance better with both.

9. The reaction time to make monocular judgments of distances is very slow, whereas binocular judgments are practically instantaneous.

10. A tendency to project one rod as nearer when actually it was the farther way was found in about 25 percent. of the cases. The phenomenon has not been explained.

11. The wide variations in the visual angle and binocular parallactic angle thresholds according to the above experiments make it evident that the two angles have nothing to do with each other.

(Abstracted from the *American Journal of Ophthalmology*, Vol. II, pp. 656-675, 1919.)

The Effects of Faulty Cranio-Spinal Form and Alignment Upon the Eyes

Lloyd Mills, M.D., F.A.C.S.

THE author calls attention to the opinion which has been commonly held that various tiltings of the head, heterophorias and heterotropias, especially the cyclophorias, were primarily due to faults of the action of the extrinsic muscles and particularly of the obliques. The possibility of faulty cranial posture as a primary result of marked cranial asymmetry or secondary to faults of spinal alignment or of actual vertical lesions acting to produce ocular torsion and thereby overaction of certain groups of extrinsic ocular muscles has never apparently been considered. The specialist on the eyes has limited his notions of ocular mechanics to the orbit and, prior to the inception of the author's work in 1915, ophthalmic and orthopedic literatures have been barren of facts dealing with such an association. Dr. Charles Low-man, an orthopedic surgeon, noted improvement or relief of eye symptoms and such reflexes as pulling, drawing or burning sensations in the neck and back of persons having cervico-dorsal lesions. These complaints were more frequent after sewing, reading, writing, and other activities requiring stabilization of the head or shoulder-girdle fixation.

It is well known that only about 10 percent. of persons may be classed as "ideally normal." About an equal number possess emmetropia and normal ocular muscle balance. Mills assumes that the eyes may be involved in these skeletal defects of balancing unequally weighted cranial halves upon the spine and that these effects may arise from reflex irritation upon the cilio-spinal sympathetic center or through compensatory action of the extrinsic ocular muscles producing compensating heterophorias and heterotropias. Also, Mills believes it logical to think that certain ocular muscles might become shortened by adaptation.

Several hundred consecutive eye cases were contrasted with consecutive cases of postural defects in children at the Crippled Children's Guild. The monocular and binocular ductions were taken together with the refractive findings: later also the fixing eye for near and distance were determined, together with ocular torsions and the cranial and facial asymmetry and the location of the plumb line passing through the external occipital protuberance and the position and degree of head tilting. In orthopedic cases, such as infantile paralysis, hip disease, and so forth, gross ocular muscle defects and irregular astigmatism occurred in the ratio of 3.2 to 1. "Left hyperphoria occurred in 72 percent. of the orthopedic cases and 61.5 percent. of the eye cases; and the characteristic ocular imbalance associated with the obvious postural imbalance was that of left hyperphoria; exophoria for distance and increased exophoria for near, due to weakness of the left internus, the right eye fixing both for near and distance, the left diverging at near, and the left eye showing torsion or cyclophoria. In the eye group it was seen that the great majority of patients complaining of sub-occipital or cervical or brachial pains showed more or less obvious postural faults and a muscle balance corresponding to that of the characteristic orthopedic cases. Every case of hyperphoria above 5 degrees in both groups showed more complicated head tilting and rotation, more obliquity of the shoulder-girdle and more marked spinal curves and rotations than were to be found in the cases of lesser ocular imbalance."

Risley (*American Journal of Ophthalmology*, 1918) and Stevens (*N. Y. Medical Journal*, 1918) have studied and reported upon the effects of cranial and facial asymmetry upon refractive defects and muscular imbalances. Stevens concluded that the lack of symmetry of ocular position associated with cranial asymmetry leads naturally to imperfect symmetry of action and to imperfections of binocular vision.

Verwey (*American Journal of Ophthalmology*, 1918) remarks upon the correction of heterophorias of low degree through inclinations of the head. de Kleijn (*Arch. neerlandaises de Physiol.*, 1918) showed that alterations in the posture of the neck of rabbits provoked definite postures of the eyeballs. Sherrington (*Brain*, London, 1918) concluded that "sensory impressions of the neck posture have probably to be added to the factors implicated in visual imperceptions of orientations as regards verticality and inclinations thereto." Sherrington emphasizes the fact that spatial perceptions are by no means purely visual but are rather "visuo-musculo-labyrinthine," the afferent nerve fibres in the extrinsic ocular muscles yielding sensory impressions which are the basis of perception of postures and movements and which aid the proprioceptive nerves of the rest of the body, especially those of the gravitational labyrinth in registering the attitude of the whole body and its relation or orientation to the vertical.

On the lateral muscular imbalance Mills writes: "The lateral muscular imbalance we consider in the main the result of cranial, orbital and facial asymmetry as affecting the relative positions and musculature of the eyes, and there is no doubt, from our demonstrations of complete ocular muscular readjustments to normal of lateral imbalances following spinal realignment, that cranial posture with regard to verticality, whether purely of spinal or of cranial origin, or the product of both, is the activating factor in this as in most ocular imbalance."

To the reviewer, the most valuable and interesting part of Dr. Mills' paper is his discussion of those cases showing 2 to 6 degrees of exophoria at distance; 9 to over 20 degrees of exophoria at near and usually variable; adduction equal to or often less than the abduction; frontal, sub-occipital and nuchal aching provoked by close work, soreness at various points along the spine and with an increase in general nervous symptoms. Some of these cases showed no refractive errors; the majority, however, had compound hyperopic astigmatism. The right eye is generally the fixing eye both for distance and near, while the left eye diverges when test objects are brought near and is higher and has its axis tilted (cyclophoria or declination). Careful orthopedic examinations show that these cases generally occur in connection with abnormal spinal twists and rotations, with irregular and painful impingements of normal or abnormally broad lateral pressures, and so forth. Mills points out that the relation of cause and effect is shown by the relief to nervous spinal and ocular symptoms following corrective measures. In many cases where abduction is weak the relief is accelerated by appropriate prism exercises, fixation exercises from improving the near balance, graduated reading and careful visual hygiene.

With much propriety Mills points out that "Two practical points of ocular hygiene arise from this investigation: 1. In the cases, which develop symptoms referred to the neck on close ocular fixation, attention should be given to correct seating, and to such cranio-cervical support and consequent relaxation that contraction of the erector spinae group cannot be maintained stiffly or at least can be minimized. 2. In those cases where occupation demands ocular fixation combined with intense shoulder-girdle fixation, such as in sewing, reading, and typing, and especially when without arm support, the symptoms are often induced more by the weight of the hands, forearms and arms dragging upon the trapezius and keeping it contracted than by the process of shoulder-girdle fixation alone. Here again the relief can be obtained by relaxation gained by correct seating, correct posture, by voluntary relaxation of the back and neck and especially by providing chairs with arms to relieve the shoulder-girdle of the pendant weight. Herein also lies the great value of the reading stand or rack which allows complete shoulder-girdle relaxation and permits the reader, as well, to assume a completely relaxed posture of head and spine."

The important conclusions of this paper are: (1) There are recorded the first demonstrations that the common faults of head position, hitherto ascribed solely to faults of action and distribution of the extrinsic ocular muscles, often may be due to structural skeletal faults original in the lower extremities or spine, which affect the eyes thru their influence upon head postures, as well as thru their effect upon the cilio-spinal sympathetic center and the sympathetic center and the sympathetic pathways. (2) Excluding conditions originating from diseases, the basic skeletal faults deemed responsible for many functional defects in the eyes and nose and for much ocular and cranial pathology, are those arising from asymmetry of the cranium in connection with the racial prevalence of right-handedness and the less common left-handedness. From this asymmetry spring orbital distortions and alterations in the positions, muscular distribution and muscular actions of the eyes, the left eye being mainly affected thru its proximity to the larger left cerebral hemisphere and the large left cranial fossae, and left hyperphoria, cyclophoria and left abductor weakness being the common muscular defects. (3) Faults of cranial posture influence the proprioceptive functions of the extrinsic ocular muscles, the retina and the muscles of the neck and undoubtedly put more strain upon the labyrinthine mechanism in their efforts to readjust the ocular position with regard to verticality or spatial orientation. (4) Stabilization of the head on the neck and shoulders is almost as essential to all intense and prolonged ocular fixation as the more limited action of the extrinsic ocular muscles. Stabilization of the shoulder-girdle is equally an essential, when finely coördinated manual work is the object of the ocular attention. Strains of this stabilizing system thru its overuse, and especially in the presence of spinal faults and uncompensated shoulder-girdle deviations, produce the distressing sub-occipital, cervical and brachial symptoms incident to reading and to many occupations. (5) Severe ocular imbalance is found more common among cases which are primarily orthopedic than among average eye cases. Cranio-spinal postural defects are found almost uniformly in the eye cases complaining of sub-occipital and nuchal aching, and are, in the main, capable of relief or cure by methods of relaxation and by appropriate orthopedic and ophthalmic procedure. As a result of such treatment we have noted the lessening and disappearance of ocular muscle imbalance and, in a few cases, the lessening or disappearance of corneal astigmatism. (6) Two logical applications of these investigations are pointed out: (a) Ambidexterity should be insisted upon during the infantile period and (b) The prevention of ocular faults resulting from faulty spinal alignment lies in the early recognition of the spinal defects.

(Abstracted from the *American Journal of Ophthalmology*, Vol. II, pages 493, 499, 1919.)

B.
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The American Journal of Physiological Optics

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Clinical and Office Methods of Testing for Color-Blindness

J. Ellis Jennings, M.D., F.A.C.S.

THE first accurate description of color-blindness was made in 1774 by Dalton, the celebrated English chemist. He was red blind and saw no difference between the color of a laurel leaf and that of a stick of red sealing wax; and the various colors of the rainbow were narrowed down to yellow and blue. Up to the year 1837 color-blindness was looked upon as a very rare affection; no practical method of investigation had been devised and the cases seen were accidently discovered. In that year Seebeck made a study of the subject and had persons arrange in the order of their resemblances to each other about 300 pieces of colored paper. In 1854 Prof. George Wilson of Edinburgh examined soldiers, students and policemen with pieces of colored paper and discovered 65 color-blind out of 1154 persons examined (5.6 per cent.). He was the first to point out that the color-blind are totally unfit to become painters, dyers, weavers, tailors, chemists, botanists, geologists; and especially seamen and railroad employees, because of the peculiar liability of the color-blind to mistake the red and green signals in common use.

In 1875 Prof. Holmgren of Sweden introducd his well known worsted test which was based on a scientific study of color-blindness with the spectroscope.

Looking into a spectroscope the normal eye sees a band of colored light which is known as the solar spectrum. We distinguish seven pure colors—*i.e.* red, orange, yellow, green, blue, indigo and violet. The red and green blind see only two colors—yellow and blue with a gray or neutral band between them. Holmgren selected as his first test color a light pure green because it is the whitest color of the spectrum and corresponds in tint to the general tone of the neutral zone. The color-blind confuse this green with pale shades of gray, brown, fawn and yellow. His second test color is purple (rose) which is an equal mixture of red and blue. The red-blind do not see the red in the rose and therefore match it with different shades of blue. The green blind match the rose with greens and gray.

The Holmgren worsted set consists of three large test skeins; green, rose, and red and about 125 small skeins made up of the following colors: red, orange, yellow, yellow-green, pure green, blue-green, blue, violet, purple, pink, brown, gray,—several shades of each color and at least five gradations of each tint from the deepest to the lightest. The pale gray shades of brown, yellow, red and pink must especially be well represented.

The Holmgren Worsted Test

Test 1. Place the whole number of colored worsteds on a clean cloth on a table in good clear daylight. Put the *light-green* test skein A at a distance of about 2 feet from the other colors and ask the candidate to select from the heap of colors all that look to him like this test skein and place them beside it. Have him understand that he is not expected to find an exact match for the test skein, but that he is to choose all the colors that appear to him of the same general color as the test skein, both those that are lighter and those that are darker in shade. If he does not easily understand what is wanted, let the examiner himself select the colors;

then, having returned them to the general heap and mixed them thoroughly with the rest of the colors, let him call on the candidate being examined to repeat the selection. This demonstration will not enable a candidate who is defective in his color-perception to select the colors correctly, and he may pick out, as looking to him like the test skein A, some greens, and also some of the gray or brown confusion colors, which will appear to him of the same general color as the test skein, only varying from it in shade. Record on the form the numbers on the tags of the colors selected as being similar to the test skein A, and also note whether the selection is prompt or hesitating.

A person with a normal color-sense will pick out the lighter and darker shades of green rapidly and without hesitation. He may, perhaps, include in his choice a few green skeins inclining to yellow or blue, but this is no evidence of color-blindness, but rather of a lack of practice with colors. The *completely color-blind*, whether to red or green, will select, with or without greens, some confusion colors—grays, drabs, stone-colors, fawns, pinks or yellows. The *incompletely* color-blind, or those with a *feeble chromatic sense*, will add to the selection of greens one or more light fawns or grays; or they may pick out a skein, hesitate, add it to the greens and then withdraw it, and so on.

When confusion colors have been selected, we know that the candidate is either completely or incompletely color-blind. In order to determine it nature and degree we employ a second test.

Test 2. Return all the colors to the heap and mix them together. Place the *rose test* skein B apart from the rest, and have the candidate select, as before, all the colors that look to him like this skein, and record the numbers of the skeins selected.

The color-blind will always select deeper colors, that is, either the light or deep shades of blue and violet. The *completely red-blind* will select blue or violet, either with or without purple. The *completely green-blind* will choose green or gray either with or without purple.

A candidate who is proved color-blind by the first test is only *incompletely* color-blind if he matches the rose with deeper purples alone.

Test 3. This test is merely supplementary to the two preceding and consists in separating the *red* skeins from the rest of the wools. The *red-blind* will select, besides the red, green and brown, shades darker than the red. The green blind will select green and brown shades lighter than the red. Only persons with marked color-blindness manifest their defect with this test.

The Holmgren test, in its original form, has been more generally used than any other, but it has some faults, and, as often used, it does not detect all the cases of serious defect in color sense. The colors soon become soiled by handling, some of the important colors may be lost, the colored skeins are often too large, so that they give a retinal image extending far beyond the central region of the retina in which acquired defects in color perception are often found, the numbers on the tags (if numbered skeins are used) may be read if not properly concealed, and the test is not well adapted to the needs of inexperienced examiners.

The Jennings Self-Recording Test

In place of the Holmgren test the Ophthalmic Section of the American Medical Association in 1916 adopted, on the recommendation of its committee, a modified form of the Holmgren test suggested by the writer. The Jennings Self-Recording test, which is virtually the Holmgren test arranged in a different form, requires less time for the examination; the candidate makes his own record as the examination proceeds; the patches of colored worsteds are small; they are protected from the light and dust when not in use; they are not handled by the candidate and so do not become soiled

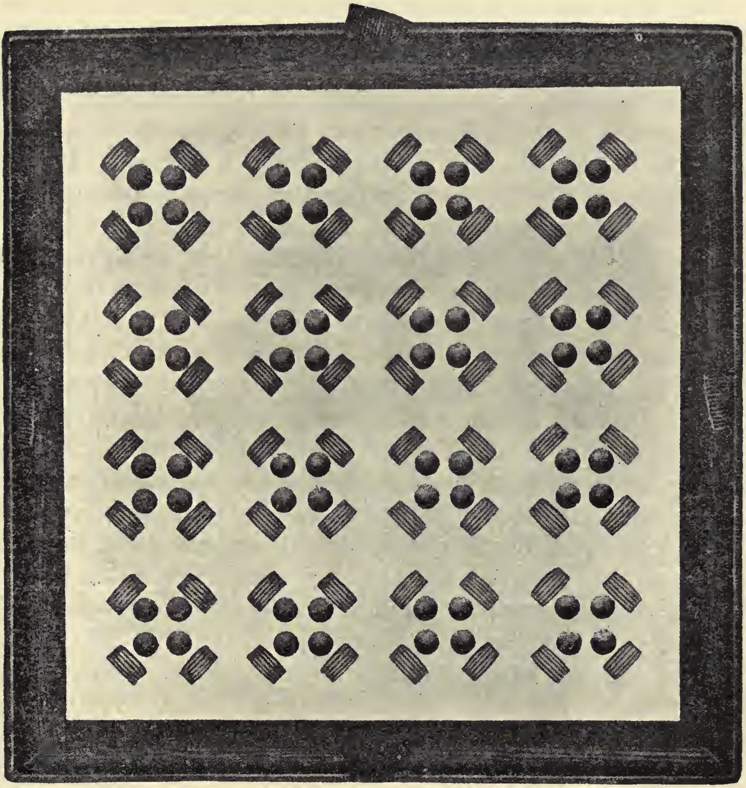
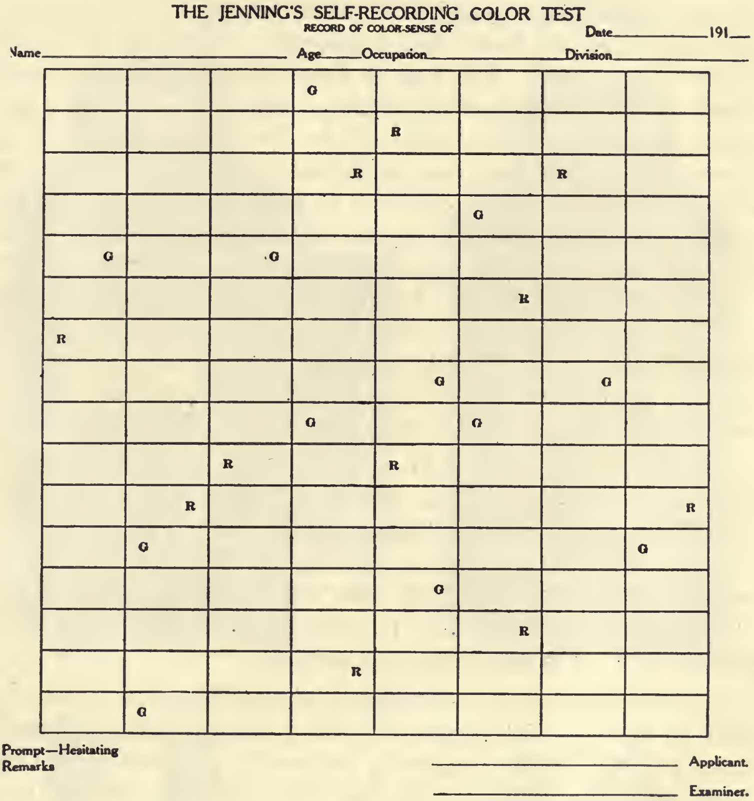


Figure 1. Jennings Self-recording Worsted test.

by use; the examiner is not called on to decide as to the qualification of the man examined, for all the records should be sent to the chief medical examiner at the central office for approval and file, thus giving greater uniformity in the results, and a better chance to have re-examinations made of doubtful cases; in case it is necessary at any time to refer to the record of an examination, the colors selected by the candidate can be seen by placing his record in the color box; the test cannot be memorized.

The Jennings test consists of a square box divided into two compartments, each half having a lid—virtually two shallow boxes with bottoms joined together. In one side of the box is "Test No. 1, Green," containing a color board made up of greens and all the different colors, shades and tints likely to be mistaken by the color-blind for green. In the other side of the box is "Test No. 2, Rose," containing a color board made up of rose and all the different colors, shades and tints likely to be mistaken by the color-blind for rose. The color boards, like the box, are square, and each board has sixty-four patches of worsteds of various colors and shades, making a total of 128 colors used in the tests. Near each patch of colored worsted is a circular opening in the color board which is for the purpose of registering the particular patch of color chosen by the candidate. This he does by inserting a stylus or pointed pencil through the opening and punching a hole in the record sheet beneath the color board. The position of the patches of color and the circular openings have been arranged in an absolutely symmetrical design, so that when the box is turned in any one of four positions, the same appearance is presented and it is impossible to know which is top or which is bottom. This prevents any memorizing of the test. The openings of the color boards are so arranged that the records of both the green and the rose tests are made on the same sheet. To the inside of one lid is attached a skein of standard green and to the inside of the other lid a skein of standard rose—these are the test colors employed.

The record sheet rests on a sheet of felting and is divided into spaces, each space corresponding to a patch of color. If the candidate has a perfect color sense, there will be a punch mark in every space marked by a letter G or R (G indicating green, and R, rose). Any punch mark in a blank space indicates a mistake. If the mistake is on a horizontal line with the letter G, the mistake was made in the *Green Test.* If the mistake was on a horizontal line with the letter



THE JENNING'S SELF-RECORDING COLOR TEST
RECORD OF COLOR-SENSE OF
Date__________191__
Name____________________ Age____Occupation____________Division____________

			G				
				R			
			R			R	
					G		
G		G					
					R		
R							
				G		G	
			G		G		
		R		R			
	R						R
	G						G
				G			
					R		
			R				
	G						

Prompt—Hesitating
Remarks
____________________ Applicant.
____________________ Examiner.

Figure 2. Record Sheet for the Jennings Test.

R, the mistake was made in the *Rose Test.* By comparing the record sheet with the color board by placing it in the box under the color board, one is able to see by the punched holes exactly what colors were selected to match the test skeins.

To Use the Jennings Test

The cover of the green side of the box is removed, the color board is lifted out, a record sheet on which the name of the candidate, his occupation and the date have been written, is inserted, and the color board is replaced. In replacing the color board, *care must be taken to see that its top, marked on the back "No. 1, Green," corresponds to the top of the record sheet.* The box is now turned around several times until all sense of direction is lost. The Green Test Skein, fastened to the inside of the box lid, is placed at a distance of 2 feet and the candidate is given the stylus or a pointed pencil and requested to look along each row of colored patches, and when he sees the test color, or one of its lighter or darker shades, he is to place the point of the stylus in the opening and punch a hole in the paper beneath. Have him understand that he is not expected to find an exact match for the test skein, but that he is to indicate all the color patches that appear to him of the same general color as the test skein, both those that are lighter and those that are darker in shade.

Having completed Test No. 1, the record sheet is removed, the cover is replaced, and the box turned over, exposing Test No. 2, the Rose. The same record sheet is placed under the rose color board, *care being taken to have the top of the record sheet and the top of the color board, marked on the back "No. 2, Rose," correspond.* The Rose Test Skein is now displayed and the test proceeds as before.

In making the test, the examiner should instruct the applicant to start at the upper left hand corner and go slowly along one row before beginning the next. Proceeding in this systematic manner he is less likely to overlook some of the sought for color. If he fails to punch several of the test colors, he may be asked to go over the test again, in order to make sure that he has not missed any. *The most important duty of the examiner is to place the color board in the box so that its top (marked on the back) corresponds to the top of the record sheet.* After the examination has been completed, the record sheet should be inspected, and a perfect test will show a punch hole in every space marked by a letter. If the applicant has punched in the proper openings, and yet punch holes appear in the blank spaces, then the color board was not placed correctly and the test must be made again.

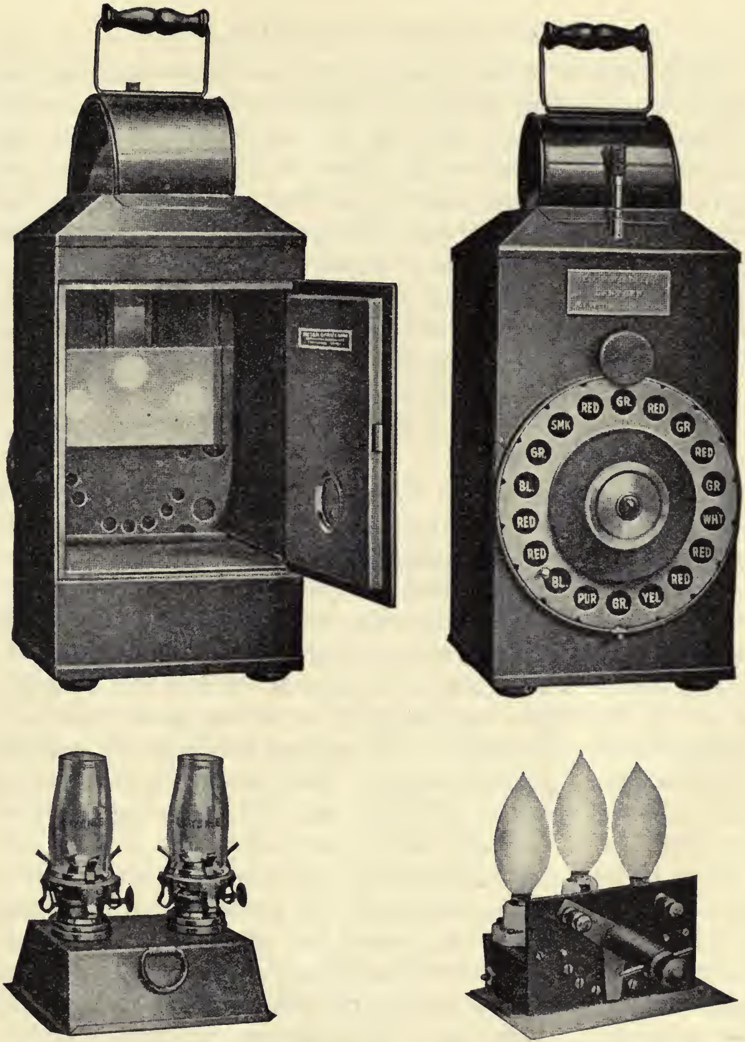


Figure 3. Williams Lantern, Model of 1914.

On the front of the lantern is a disk carrying eighteen glasses, many of them pieces of signal glasses. In the center of the disk is a knob which moves the revolving shutter inside the lantern by which the size and number of the openings are regulated.

The Williams Lantern Test

In addition to the worsted test it is necessary that another test with a lantern should be used in every case in order to determine the acuteness of the color perception in the central portion of the retina where the light from a distant signal is focused, and also the ability of the candidate to recognize and name correctly and promptly the colors of the signals he will have to use at night.

In the cases of *acquired* defect in color sense, due to excessive use of tobacco or alcohol, or other causes, the changes in the retina are often confined (in the earlier stages) to a small central portion of the retina, and such defects may not be recognized with the ordinary worsted test but will be found with the lantern.

The colors transmitted by the signal glasses in common use (especially the green and yellow glasses) are far from being pure colors; the green usually has some blue and sometimes a little red mixed with the green, and the yellow often transmits some red in addition to the yellow. It is therefore important that a test should be made in which service colors, in addition to others, are used, in order to find out whether or not the candidate can name them, or designate their use promptly and accurately. The remark made in the preface must be kept in mind, namely, that persons with marked defect for red or green will often see the red, orange, yellow and green colors blended into a sort of yellow, and in the lantern test they will often call a green or red light, yellow, and this mistake is more frequently made than the calling of a red light green or vice versa, though this is often done. In the worsted test no color names are used; when properly made it is simply a test by comparison with two test colors; but with the lantern test it is important to know whether the candidate is able to give promptly to the sensation he receives from the signal colors red, yellow, green, blue and white, the name or use which is given to those colors by persons who have normal color sense. Persons with defective color sense (especially for red and green, which is the kind most often found) will often learn to differentiate between the red and green by a difference in the intensity of these colors, and they may learn to give the correct names to red and green, especially in a field test in which the choice may be between these colors only. Such a person may call the colors correctly when the glasses are clean, the lights burning properly and the atmosphere clear, but he cannot be depended on to recognize them properly under all the varying conditions of service. Two neutral glasses of different shades have been added to the lantern so that any color in the disk, when seen through the middle opening, can be seen with three different intensities, and in this way, simply by varying the intensity of the color, persons will be found who will call a red light green or vice versa.

On the front of the lantern is a disk carrying eighteen glasses. There are seven reds of different shades, five greens, two blues, one purple, one yellow, one smoke, and one uncolored glass. Behind this disk (in the model of 1914) is a revolving diaphragm shutter so arranged that by turning a knob on the front of the lantern, the colors in the disk can be shown one at a time, or two or three at a time, so that the effect of the colors can be seen singly or in simultaneous contrast. With this shutter and the revolution of the disk carrying the colors, fifty-four different settings or combinations of these lights can be made, not counting the differences in the three sizes of the illuminated areas which can be shown, or the difference in the intensity of the lights which can be changed by the insertion of the neutral glasses or by the rheostat in the base of the electric lamp. Under each color, when shown in the disk, is an illuminated number, screened from the candidate but seen by the examiner, so that the examiner can note on his record, as the examination proceeds, the number of the color shown and the name given to it by the candidate.

The room being darkened the lamps are lighted in the lantern and it is placed 20 feet from the person to be examined and on a level with his head, the side of the lantern carrying the disk with the colored glasses facing directly toward him. The revolving shutter, regulated by the knob in the middle of the disk, is so placed that two lights are shown at one time through the largest openings. In order to do this and have the colors shown to the applicant in the sequence as printed on the standard record form appended to this report, the shutters are placed so that three lights are shown at one time (Nos. 1, 11, 3) with the largest openings, and then cut out the middle opening by means of the knob above the disk. The person being examined is then asked to call aloud the name of each of the colors shown and to designate their position, for instance "left red, right red." The disk is then turned with the glasses (not too rapidly) until all the colors have been shown. In order to avoid memorizing, the disk may be turned in the reverse order, or it may be set so that some other numbers than 1 and 3 are the ones first shown. The examiner will note on the record blank (shown at the end of this report), as the examination proceeds, a small circle O (for O. K.) under the number on the form corresponding to the illuminated number under the color shown, in case the candidate gives the correct name to that color. In case of error the examiner will write under such number the name given. In each space of the form is a letter R, G, Y, B, P or W, which is the initial letter of the color red, green, yellow, blue, purple or white, corresponding to the number over that space.

A complete record form will then show a series of circles for each color called correctly, and the name written out in full where mistakes have been made. This name can be compared with the initial of the true color for that number printed on the form. This will be a saving of time over the plan of writing out the name of each color as called. After showing all the colors with the two largest openings, the shutters are revolved so as to show only one light at a time through the medium size opening, and note is made as before of the colors shown and the names given. At the top of the lantern is a sliding rod which controls the position of the two neutral tinted glasses, of medium and darker shade, which can be placed before the middle opening, in order to change the intensity of the colors shown there. For this test the middle opening should be at full size and the other two openings closed. This can be arranged by having the shutters placed so that three full size openings are shown at one time; then, by rotating the knob at the center of the disk two clicks to the left, the center opening will be shown alone. By revolving the disk and sliding either the medium or darker tinted neutral glass before it, any color in the disk can be shown with three different intensities, and a person with defective color vision, who depends on the intensity to judge the color, will often call a red light green, or a green light red, when the intensity is so altered. The size of the middle light area can be regulated by the knob *over* the disk, but when using the neutral tinted glasses, the largest opening should be used.

Doubtful, or appealed, cases should also be tested with three lights showing at one time.

A candidate should be rejected:

1. If he calls a red light green or white.
2. If he calls a green light red or white.
3. If he calls a white light red or green.

If he calls a yellow light red or green, or calls a red or green light yellow, he should be referred to the chief medical examiner for re-examination.

With the smallest opening in the shutter it will often be found that No. 7 (cobalt blue) or No. 16 (red or purple) cut off so much light that it is difficult to recognize them.

For ordinary use it will be sufficient to use either the medium or the largest openings in the shutter. The medium size opening with a diameter of one-fourth inch, at a distance of 20 feet from the eye, will give a retinal image small enough to test the color sense of the central portion of the retina, and at the same time large enough to be easily recognized by normal eyes.

With the lantern test it is often possible to clear up a question of doubt which may exist after the worsted test, and to show in a more convincing way the dangerous quality of the defect in color vision; for when a man calls a red light green or a green light red, or a red or green light white, there is no question as to the dangerous condition of his defective color sense.

When the No. 7 cobalt blue glass is used there may be some persons who will see it as a blue center surrounded by a red border, and others as a red center surrounded by a blue border. This is caused by the fact that the cobalt glass transmits both blue and also some red light, and persons who are near sighted will see it as a red center with blue border, and those who are far sighted will see it as a blue center with a red border; this is not due to any defect in color perception but only to the fact that the red rays and the blue rays are brought to a focus at different points in the eye, and the arrangement of the colors varies with the different refractive conditions of the eye.

In making the lantern test the examiner must be careful, as the test proceeds, not to make any remarks which would indicate whether the answer was right or wrong, but simply make a record on the form with an O for the correct naming of the color, or write the name given when a mistake was made.

Stilling's Plates

Stilling seeks to deprive the color-blind of any aid in matching colors by selecting those which appear identical not only in tint but also in intensity of light. Aided by a red-green blind painter and a blue-yellow blind teacher he was able to determine the interchangeable colors. On a colored surface of convenient size he painted a spot of the color mistaken for it; he then toned or modified this spot until the color-blind eye could not distinguish between the spot and the surface. Stilling then constructed ten plates, each plate containing four squares filled with small colored spots among which other spots in a confusion color are so arranged as to represent a letter or figure.

In using this test, the test plate is held in a good light and the candidate required to read aloud the letter or figure. If he is defective, he is unable to distinguish the dots forming the figure from those forming the background and so cannot read the figure. Stilling's plates are of practical value.

Nagel's Card Test

Nagel's test consists of a set of cards each having a series of small colored disks arranged in a circle. On some cards the disks are all of one color but of slightly different shades. On others, confusion colors are mixed in with the test colors.

In making the test the candidate is asked to state which cards have disks of one color, and then to indicate the test color on those cards which also have confusion colors. In this way it is possible to ascertain whether he is color-blind and to what class he belongs.

Nagel's Anomaloscope

The anomaloscope consists of a telescopic tube mounted on a metal base and an alcohol lamp with an asbestos chimney. As theobserver looks into the eyepieceof the instrument he sees a color-field which is divided into an upper and lower half. The lower half of the field is illuminated with sodium yellow and the upper half is illuminated with a mixture of lithium red and thallium green. By means of a screw operated with the right hand the brightness of the lower yellow half of the field may be altered. A left hand screw changes the red-green mixture of the upper half of the field from a pure red to a yellow and then to a pure green.

With this apparatus it is possible to get a match between the pure sodium yellow of the lower half of the field and a yellow in the upper half of the field made by a mixture of red and green. To the normal eye this match is obtained when the right hand screw registers 14 and the left hand screw registers 60. The color-blind match the yellow of the lower

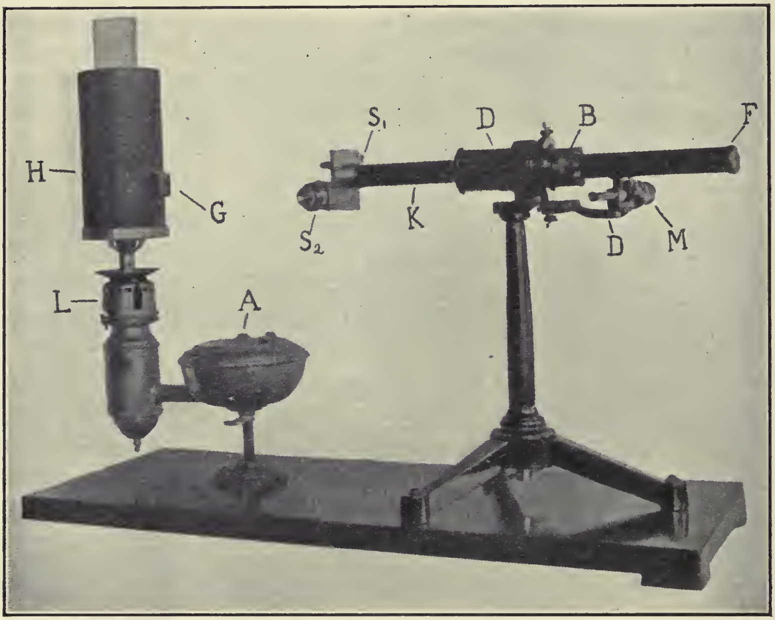


Figure 4. Nagel's Anomaloscope for Testing Color Vision.

K, collimator tube; F, eyepiece tube; D, prism; M and lower D, screws to control the position of the eyepiece tube; B, diaphragm to alter size of visual field; A, L, H, illumination system with asbestos chimney; G, ground glass plate used as the source of illumination for the anomaloscope; S_1 right-hand screw controlling width of upper slit and lower half of field as seen at the eyepiece. S_2 controls the width of the two coupled slits and the upper half of the field as seen with the eyepiece. Through one slit light is transmitted through the prism, which, when seen at the eyepiece, corresponds to the lithium red; through the other slit comes the thallium green. By moving the screw S_2 the upper half of the field is illuminated by a proportional amount of the red-green mixture, from a red to a yellow and then to a green.

field with the various abnormal mixtures of red and green and even with a pure red or a pure green of the upper field.

In making the examination a pure red in contrast to the yellow is shown. If there is any brightness of the yellow which appears of the same color and brightness as the red, the subject is color-blind. If he gets no match between the red and yellow, we now mix green with the red to find with what mixture of red and green and with what brightness of the sodium yellow a match is obtained. The cost and delicacy of the instrument, the time required for the examination and the fact that it must be used by a skilful examiner to insure good results will, in the writer's opinion, prevent the anomaloscope from being used in the routine examination of large numbers. On the other hand, it gives very valuable information as a control instrument in the re-examination of doubtful cases.

Of the tests for detecting color-blindness described in this article the ones most generally used in this country are the *worsted test* and the *lantern test. Both* of them should be used in the ordinary routine examination of the color sense as it is not safe to rely on one test alone. If the candidate can pass both tests it is reasonably certain that he is not color-blind. In doubtful cases or upon appeal the man should be referred to the chief medical examiner who will repeat the worsted and lantern tests and use in addition any of the other tests described with which he may be provided.

St. Louis, Mo.

Persistence of Vision and the Primary Color Sensations

Frank Allen, Ph.D., F.R.S.C.

WITH the exception of astronomy perhaps no branch of science extends so far back in history as the study of color vision. The reason for this is obvious. Color in nature is displayed on so magnificent a scale that minds at all observant could not fail to be impressed. The records of Babylon and of Egypt do not give much information of a scientific nature, due perhaps to their custom of jealously confining such knowledge to the guilds of priests. But the Greek philosophers, from Pythagoras onward, with their marvelous aptitude for speculative inquiry, manifested the most extraordinary ingenuity in devising explanations regarding the origin of color and the nature of its perception. Pythagoras entertained a corpuscular theory of light. Empedocles and Plato imagined vision to be a species of the sensation of touch excited by invisible feelers having their origin in the eye; Epicurus believed that we see by the intervention of light as we feel an object by means of a stick; Aristotle urged that color is due to the mixture of darkness and white light; or, in modern terms, that the mixture of something with nothing in varying proportions gives an infinite variety of something else. This hypothesis of Aristotle was enthusiastically adopted by the German poet Goethe and advocated by him with an accompaniment of highly vituperative abuse directed against the illustrious Newton and his theory of colors

Despite manifold attempts to explore the fascinating field of color, the subject lay wrapped in mystery until Newton with his prism dispersed white light into its color components, and enunciated the simple but sufficient principle that "to the same degree of refrangibility ever belongs the same color, and to the same color ever belongs the same degree of refrangibility." The uniform failure of all attempts to explain colors before Newton's success lay in the universal assumption that white light was a pure entity in itself. Once the fact was recognized that white light is a mixture of colors, progress became rapid and certain.

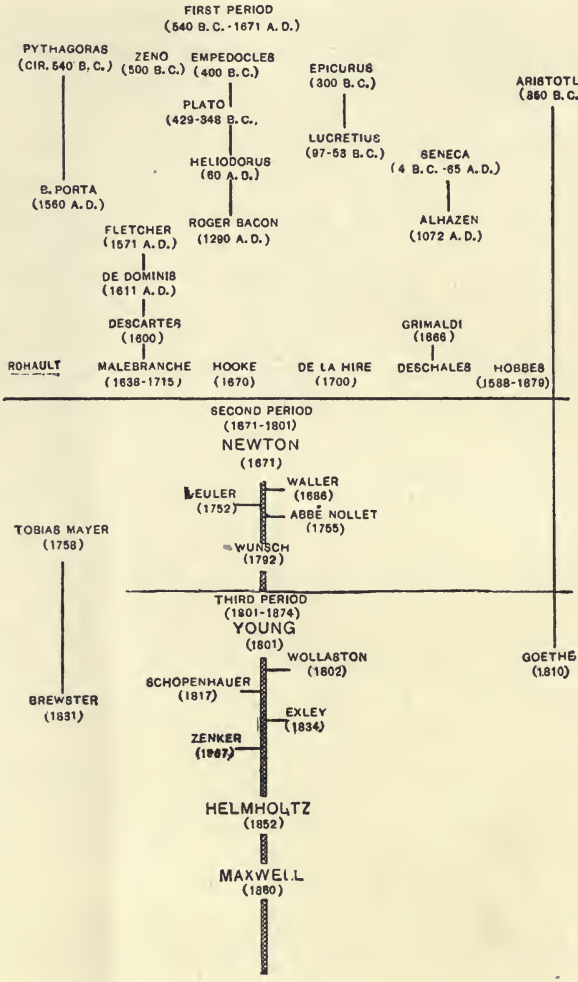
We do not need to discuss here the history of Newton's corpuscular theory of light and its triumphant rival, the undulatory theory of Huygens. But it will not be out of harmony with the title of this paper to note a peculiar use which was made of the persistence of vision. One objection urged against the idea that light consisted of streams of swiftly moving corpuscles was that myriads of collisions would occur especially when two streams of light crossed each other's path. But one ingenious writer pointed out that if each "lucid point" on the sun emitted only one hundred and fifty corpuscles per second, they would still give a continuous impression of light, owing to the persistence of vision in the retina, and at the same time the particles of light would be over one thousand miles apart. Surely by this happy supposition the chances of collision were reduced sufficiently to satisfy the most exacting criticism.

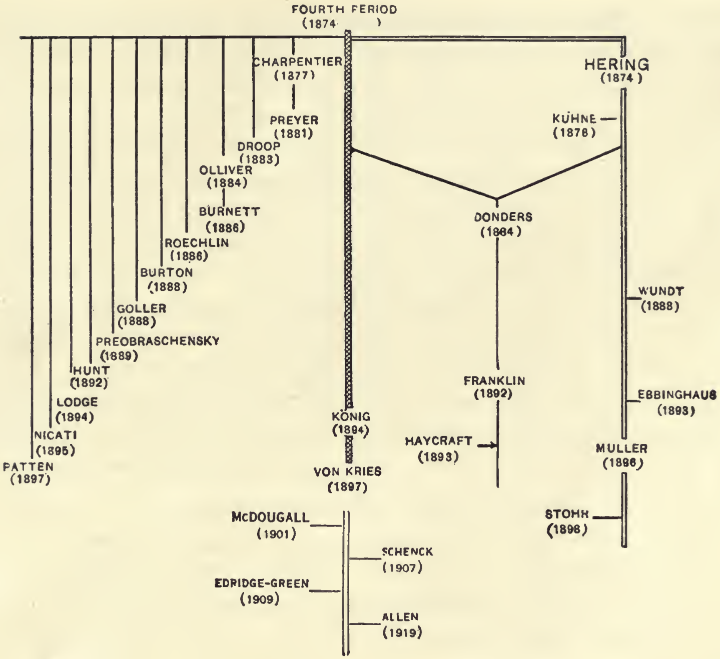
It is doubtful if any subject in science has been the cause of so many speculations and theories. Nor are the controversies by any means settled today. Scarcely a year passes without a new theory of color vision being advanced by some ambitious scientist whether he be a physicist, psychologist or physiologist. In many cases the paper announcing the birth of the new theory constitutes also its obituary notice. The sciences of physics and chemistry, of physiology and psychology, have been diligently searched for principles, one seemingly more inapplicable than another in order to account for the transformation of the energy of the ethereal waves into the diversified hues of color.

To the general problem of vision was added the interesting and important fact that it was necessary to assume only a limited number of color sensations to provide for the perception of an unlimited number of hues and tints of color. It is largely conflicting views as to the number and nature

Table I

HYPOTHESES OF COLOR VISION





of these primary color processes that cause the battlefield of color vision to be so littered with the remains of the dialectically slain.

That this is no mere figure of speech may be seen from the preceding genealogical tree of color vision which I published in the *Physical Review.* This also has the advantage of exhibiting the main line of development from Newton, and the subsidiary line due to Hering together with the positions of theories of secondary importance. Some guiding principle such as this diagram affords will enable the reader of the voluminous literature of color vision to trace his steps without confusion.

The main controversy today is between the theory of Hering and that of Young modified by Maxwell, Helmholtz and others. As is well known the latter and far older theory, adopted generally by physicists, provides for three color sensations, red, green, and either blue or violet; while the theory of Hering adopted largely by psychologists provides three antagonistic pairs of color sensations, red-green, yellow-blue, and white-black. To admit blackness to the rank of sensations seems to the physicist an impossibility in view of the fact that darkness is the absence of light energy. Still so long as crucial experiments to determine the number of primary sensations are lacking no end to the controversy is apparent. I am convinced however that the experiments on the persistence of vision which I have conducted for some years speak on this point with the utmost decision.

As the different colors of the spectrum are designated in this paper by their wave-lengths, it will be useful to remember that the limiting wave-lengths according to Listing are:

Table of Colors and Wave-lengths

.723μ to .647μ—Red
.647μ to .585μ—Orange
.585μ to .575μ—Yellow
.575μ to .492μ—Green
.492μ to .455μ—Blue
.455μ to .424μ—Indigo
.424μ to .397μ—Violet

The apparatus used in all my researches in color vision was arranged according to the diagram in Fig. 1. Light

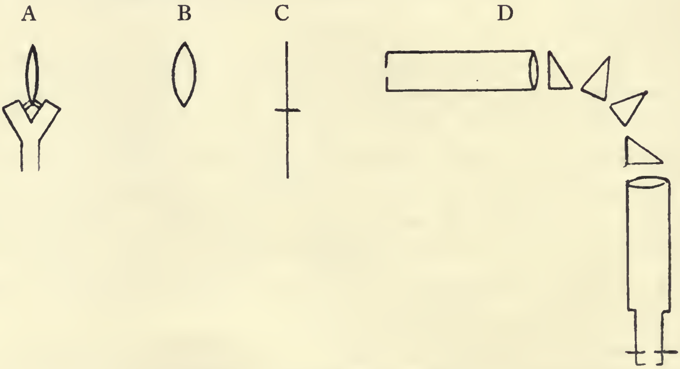


Figure 1. Ensemble of Apparatus.
A, flame; *B*, lens; *C*, disc and *D*, spectrometer.

from an acetylene flame passed through a disk with two opposite open sectors of ninety degrees each, whose speed of rotation was recorded electrically upon a chronograph reading to the ten-thousandth part of a second. The flickering light entered a spectrometer and was viewed as a spectrum in an eyepiece with adjustable shutters which enabled all the spectrum to be cut off except a narrow vertical band of the desired wave-length. In making measurements the speed of the disk was regulated so that the flickering of the light in the eyepiece became just imperceptible and was then recorded. One quarter of the time for one complete rotation of the disk is therefore the measure of the persistence of the vision, or the duration of the undiminished intensity of light upon the retina. By many writers this is called the critical frequency of flicker.

When it became necessary to fatigue the eye by exposing it to some bright spectral color of known wave-length, a second spectrometer was used with an arc light as the source of color. An eyepiece with adjustable shutters isolated a suitable band of the spectrum which was used to fatigue the eye with which observations of the persistence of vision were made. An interval of three minutes was allowed for the fatiguing process before each measurement of the persistence of vision was taken upon the colors in the first spectrometer. In this way a persistency curve for the whole spectrum was obtained which can be compared with a normal curve previously determined when the eye was adapted for diffused daylight.

The first question that arises is: Are we justified in assuming the retina to be normal when in diffused daylight? It was formerly thought that the normal retina was obtained only after resting it in complete darkness. Experiments made under various conditions of adaptation have altogether changed this idea.

The writer has made a series of persistency curves by resting the eye, (a) in a dimly lightly "dark-room;" (b)

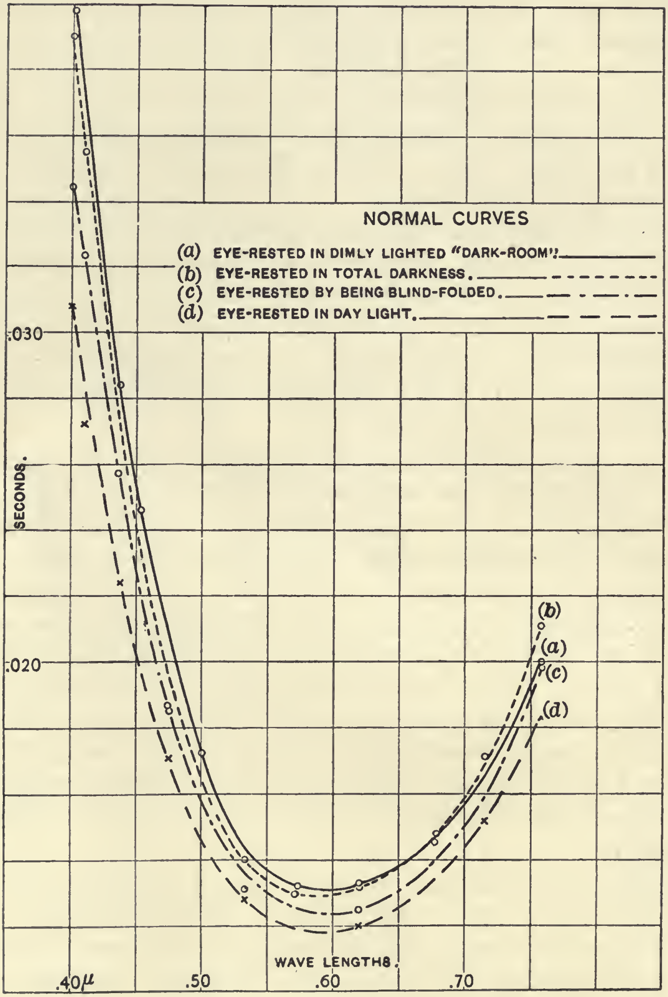


Figure 2. Persistency Curves through Resting the Eye.

in total darkness; (c) by being blindfolded; (d) in diffused daylight. These curves are shown in Fig. 2. In the first three cases the values of the duration of color impressions are greater than for daylight adaptation, the greatest difference being obtained when the eye was rested in partial darkness. This is probably due to the fatiguing of the retina by the effort to distinguish dimly illuminated objects. If we compare this figure with those obtained later when the eye was fatigued with different colors it will be noticed that the abnormal curves are always elevated above the normal. Whether, then, the retina is under the influence of direct rays of light or of darkness it is in an abnormal condition.

By comparing the amount of elevation of the three curves in this figure it is found that the values of the persistency increase from three per cent in the orange to twelve per cent in the extreme red and to thirty per cent in the extreme violet. Therefore the change in the sensitiveness for light which is produced in a retina placed in the dark is not equal for rays of different refrangibility.

The adaptation of the retina in the darkness is not sudden but progressive. Some experiments were made to determine this. The time of the persistence of vision for the normal retina was measured for the four colors $.650\mu$, $.567\mu$, $.505\mu$, and $.463\mu$. Then the eye was blindfolded for intervals of one, three, five, ten and fifteen minutes, and corresponding persistency measurements were made after each. A series of curves of the "saturation" type was obtained which are shown in Fig. 3. As far as the persistence of vision is concerned the saturation point is reached in five minutes. The delicacy of this system of measuring is well shown in the curve for the wave length 0.567μ where the whole curve is confined within the limits of one one-thousandth of a second.

A series of nine persistency curves was made for spectra of varying degrees of luminosity or brightness. These are shown in Fig. 4, the curve for the brightest spectrum being the lowest. These curves are all of the same type, but it

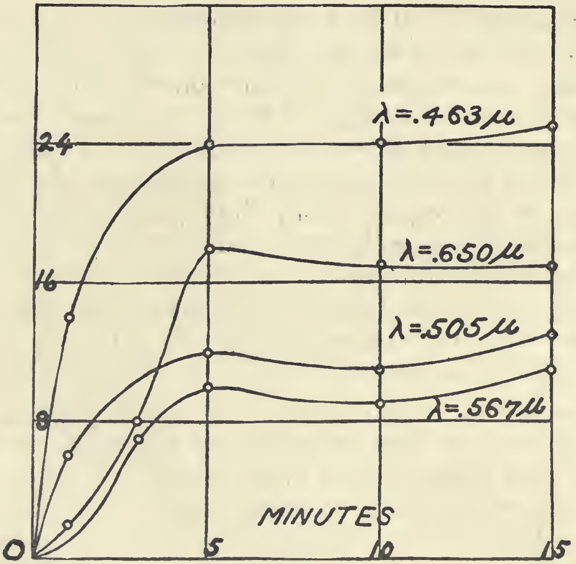


Figure 3. A Series of Curves of the "Saturation" Type.

will be noticed that the lowest point shifts gradually but slightly towards the violet as the spectrum gets less intense. As the lowest point of the curve corresponds to the brightest part of the spectrum, we have here an illustration of the Purkinje effect, viz: that the brightest point of the spectrum is not fixed but varies in position with the brightness, changing from yellow to the green as the spectrum becomes lowered in intensity.

There is a law discovered independently by two scientists, Ferry and Porter, which connects the time of persistence of vision with the luminosity of the light,

$$T = \frac{1}{k \log L}$$

where T is the time, L, the luminosity and k, a constant.

By applying this law to the persistency curves in Fig. 4, we can get a corresponding set of luminosity curves for the same series of spectra we have just been considering. These are shown in Fig. 5. The order of curves is now reversed and the luminosity curve for the brightest spectrum is now the highest, and that for the dimmest spectrum the lowest. It will be noticed how remarkable is the magnitude of the lowering in brightness at the middle of the spectrum compared with the two ends. It would also seem likely that before the spectrum entirely disappears the luminosity curve would become a straight horizontal line.

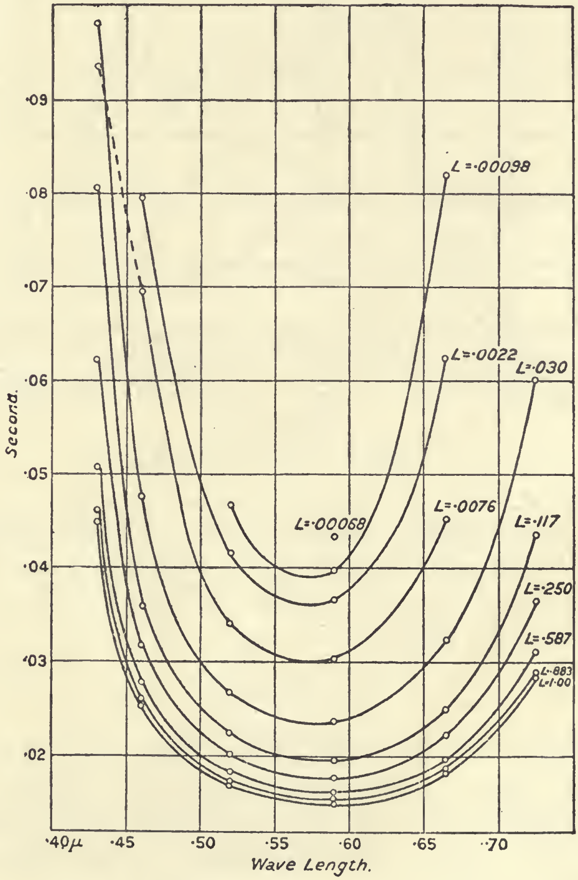


Figure 4. Persistency Curves for Spectra of Varying Degrees of Luminosity.

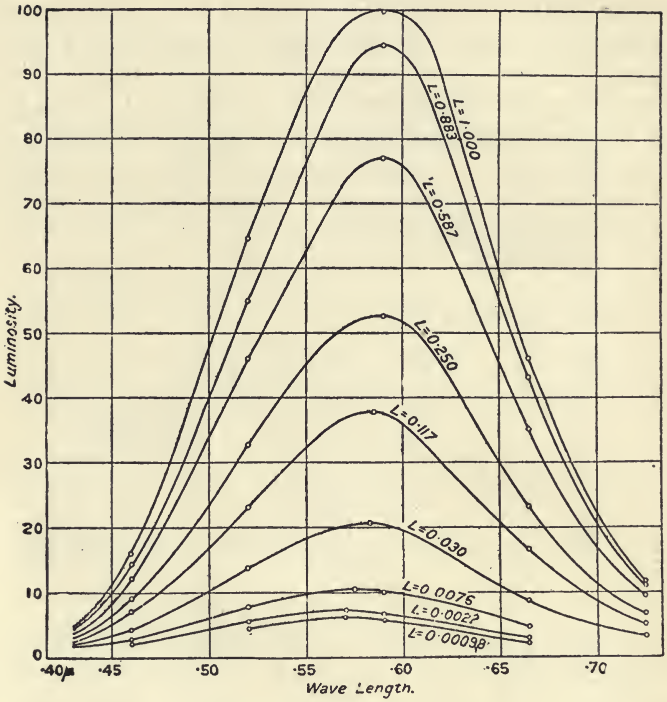


Figure 5. Luminosity Curves.

If, now, for any one wave-length we take the reciprocals of the corresponding values of the persistence of vision for each of the nine curves in Fig. 4. they will, when plotted, give a series of curves as shown in Fig. 6. These curves conform to the equation

$$\frac{1}{T} = k' \log L$$

Each of these curves consists of two straight lines of different slope, the change in direction occurring very abruptly. The slope of the lower parts of the curves varies in an extraordinary manner, that for the wave-length 0.430μ being quite horizontal.

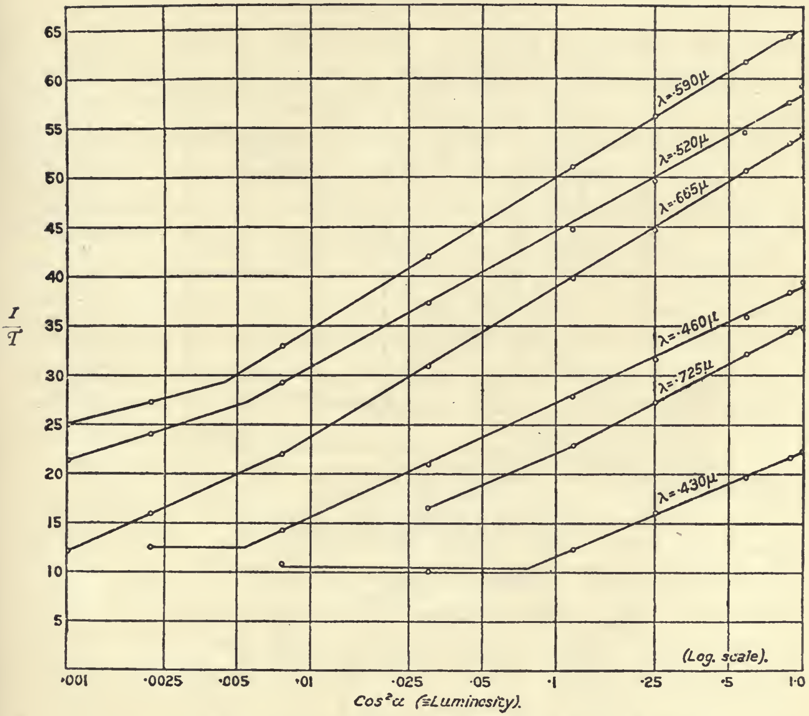


Figure 6. The Relationship between the Reciprocal of the Persistence of Vision Values and the Luminosity.

The explanation of this curious phenomenon is afforded by the duplicity theory of Von Kries, according to which the retinal cones are the parts that function in the perception of very bright light and colors, while the rods perform similar functions for dim light. The upper part of each curve therefore is for cone vision and the lower is for rod vision. The change in direction of the curve shows that the change from one type of vision to the other takes place very abruptly. From the fact that the lower part of the curve for the wave-length 0.430_{μ} is horizontal it would appear that below a certain intensity a change in luminosity does not affect the persistence of vision to any extent.

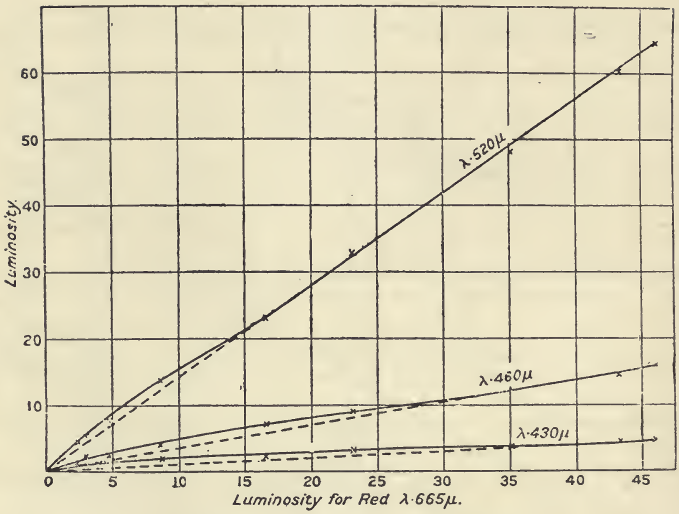


Figure 7. The Purkinje Phenomenon.

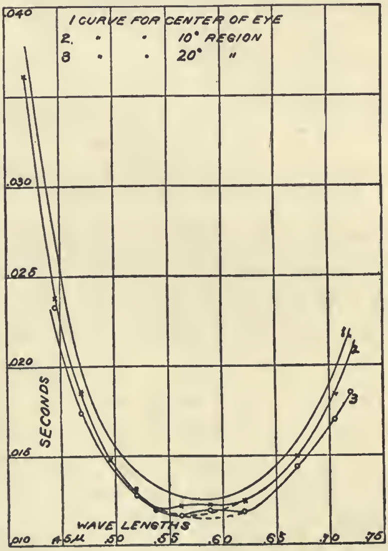


Figure 8. Curve for the Peripheral and Central Persistence of Vision.

The Purkinje phenomenon can also be shown in a very effective manner by the curves in Fig. 7. These are obtained by plotting the values of the luminosity of red of wave-length .665μ on the horizontal scale as the standard of reference, and the corresponding luminosities of the colors .520μ, .460μ, and .430μ, on the vertical scale. If, for example, the luminosity of green, .520μ, increased exactly as that for red, .665μ, the result ought to give a straight line. This is so, as the upper part of the curve indicates, for the greater luminosities; but for the smaller the curve is no longer straight but curved as shown by comparing the continuous and dotted curves in the figure. The same reasoning applies to the other two colors.

These results, as well as the bulk of the measurements described in this paper, were obtained for the center of the retina. The peripheral portions of the retina, however, have their own peculiar and distinctive visual properties. The writer has obtained two curves which show some differences between the center and periphery of the retina as regards persistence of vision. The measurements were made by inclining the eye so that the flickering light fell, first, ten degrees, second, twenty degrees, from the center of the retina on the temporal side. The curves are shown in Fig. 8, in comparison with a normal curve for the center of the eye. Both curves, Nos. 2 and 3, are below the normal indicating greater sensitiveness of the retinal periphery as regards the flickerng light of all colors. Since the lowest point of the curve corresponds to the brightest point of the spectrum we see that, to the peripheral retina, the brightest light is not the yellow but the green.

It will be noticed that each peripheral curve has an elevation in the greenish-yellow part of the spectrum. The significance of this may be thus explained. In direct vision the light rays fall upon the macula lutea, or yellow spot, where the greatest distinctness of vision occurs. This spot,

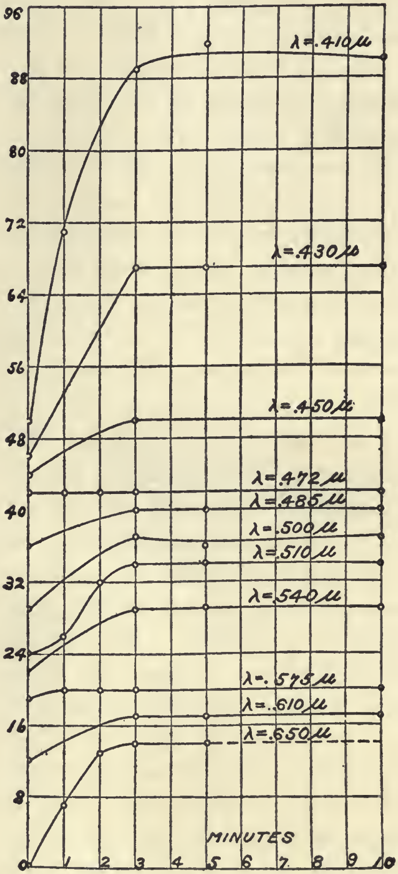


Figure 9. Persistence of Vision after Fatiguing the Eye with Various Colored Lights.

however, is small, and would not be touched by light falling on the outer regions. The macula lutea contains a yellow pigment, but no visual purple, while the retina in other parts has only this latter substance. Visual purple absorbs and is

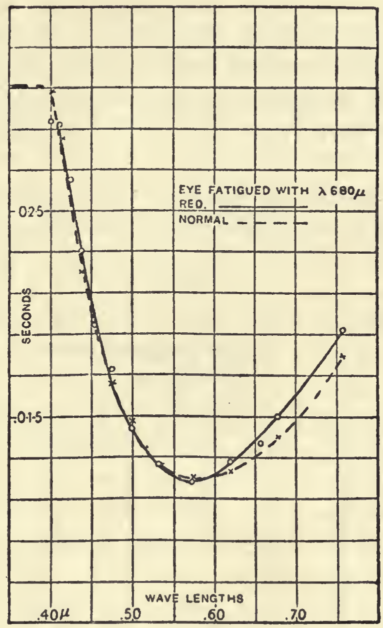


Figure 10. Retina Fatigued with
Pure Red Light.

bleached by light of all colors but in amounts varying with the wave-length, the absorption being very slight in the red and greatest in the yellowish-green, which has also the most rapid bleaching effect. The region of the spectrum, therefore, which is most absorbed by the visual purple coincides with the elevations. This shows that some of the light falling on the retinal periphery is absorbed by the visual purple and is of no service in causing vision.

We have already seen that the darkness adaptation of the retina is progressive in character. Similar studies were also made for the development of retinal fatigue when the eye was exposed to various colored lights obtained from the spectrum of an arc light. Measurements of the persistence of vision were made after fatiguing intervals of one, two, three, five and ten minutes. The results are shown in Fig.9 for eleven different colors which are indicated on the curves. The maximum degree of fatigue is obtained in three minutes. This is two minutes less than the time required for darkness adaptation.

The normal value for each of these curves is the point where it cuts the vertical axis of the diagram for zero (0)

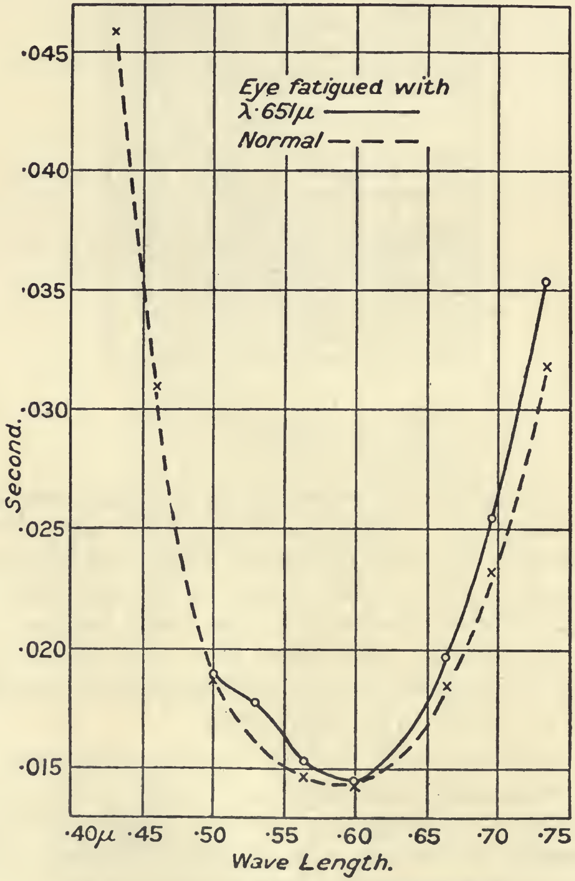


Figure 11. Retina Fatigued with Orange Light.

minutes. The interval between the lowest and highest values of the curves varies greatly, and in the case of blue, .472μ. and yellow, .575μ, it becomes zero so that these two curves are straight horizontal lines. This result indicates that, as far as the measurement of the persistence of vision is concerned, these two colors do not cause retinal fatigue. The significance of this curious phenomenon was not realized until the writer discovered the transition points in the spectrum which are now to be discussed.

A long series of persistency curves was made under the following conditions. A certain color in an arc light spectrum was isolated in a spectrometer as described above and the eye kept constantly fatigued by it. Then with the retina in this condition persistency measurements were made at intervals throughout a second spectrum. These values of the persistency were then plotted in comparison with a persistency curve made on the same spectrum with the eye in a normal condition. The places of coincidence of the two curves with, and departure from, one another give important evidence concerning the nature of the processes involved in the vision of colors.

The writer has obtained seventeen sets of these curves for the same number of different fatiguing portions of the spectrum from red to violet. By comparing these it is proved that the number of fundamental color sensations is three, viz: red, green, and violet, and the limits of wave-length between which these sensations lie are also accurately determined.

When the eye is fatigued with a pure red of wave-length, .680μ, a persistency curve is obtained which is shown by the continuous line in Fig. 10, the dotted curve being always that for the eye when in its normal conditions. The figure shows that the two curves coincide from the violet end of the spectrum to the wave-length .60μ, which is in the middle of the orange color, and then they diverge to the end of the red. In other words, fatiguing the retina with a narrow band of pure spectral red, the center of which has a wave-length of .680μ, affects only that process in the eye which causes the sensation of red and orange, and has no measurable effect on the green and violet processes. Precisely the same effect was obtained when the fatiguing color was .670μ, which is also a pure red. As the curves for these two fatiguing colors are of the same character, only one of them is reproduced here.

When the fatiguing color was .651μ, in the orange, which all color theorists agree is a compound sensation, the character of the curve experiences a radical change. This is shown in Fig. 11. Comparison of the two curves in this figure exhibits the same elevation in the red as in Fig. 10, and also shows an additional elevation in the part of the curve corresponding to the green region of the spectrum. Therefore when the retina is acted upon by a pure orange color, the red and the green perception processes are both fatigued, but the visual mechanism for the violet sensation is not disturbed. Persistency curves were taken also when the fatiguing colors were .625μ, .620μ, .589μ, and .577μ., all of which lie in the orange and yellow regions of the spectrum. In these four cases the curves obtained are similar to that shown in Fig 11.

Since for the red colors curves with one elevation were obtained, and also since for orange and yellow colors curves with two elevations resulted, there ought to be a fatiguing color which would mark the transition from one type to the other. Such a point was found to exist at the color whose wave-length is .660μ, which may be called the first transition point in the spectrum. It was discovered that four such transition points exist in the spectrum, the exact number there should be according to the three-color theory of chromatic vision.

The curve obtained for the transition color, .660μ, is shown in Fig. 12 and is found to have no elevations at all, but to be coincident with the normal curve throughout its length. We are justified in inferring from these curves that the colors of longer wave-length than that of the transition point, *viz:* .660$_\mu$, give rise to the sensation of pure red, and that they do not measurably affect the primary processess for green and violet colors. The fundamental red sensation must therefore lie between the red end of the spectrum and

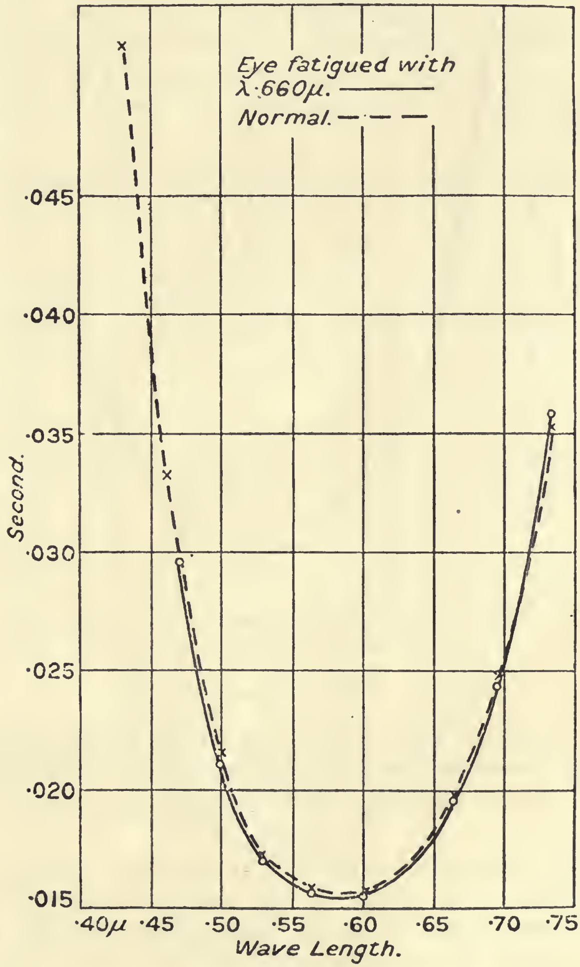


Figure 12. Retina Fatigued with a Transition Color.

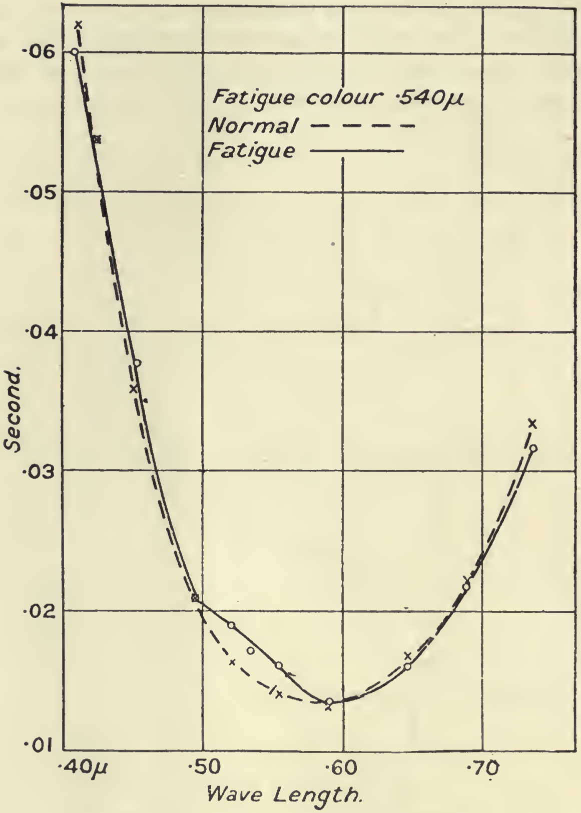


Figure 13. Retina Fatigued with Green.

the first transition point .660μ. Up to the present time the writer has found no way to determine the wave-length of the fundamental red color with any greater precision than this.

Another problem in color vision may be resolved from these curves. The cause of the sharp division of color-theorists into rival camps is largely the question as to whether yellow is a simple or a compound sensation. In purity of appearance it apparently demands recognition as a primary sensation as much as yellow or green. The curves for the colors .651μ, .625μ. .620μ, .589μ and .577μ, all of which lie in the orange and yellow regions, are of precisely the same character as that shown in Fig. 11. Since the yellow fatiguing colors affect the red and green sensations in the same manner and to the same degree as do the orange colors, they must be of the same fundamental nature. That is, yellow must be a compound sensation. Surely experiments like these, which any one may perform for himself, are more

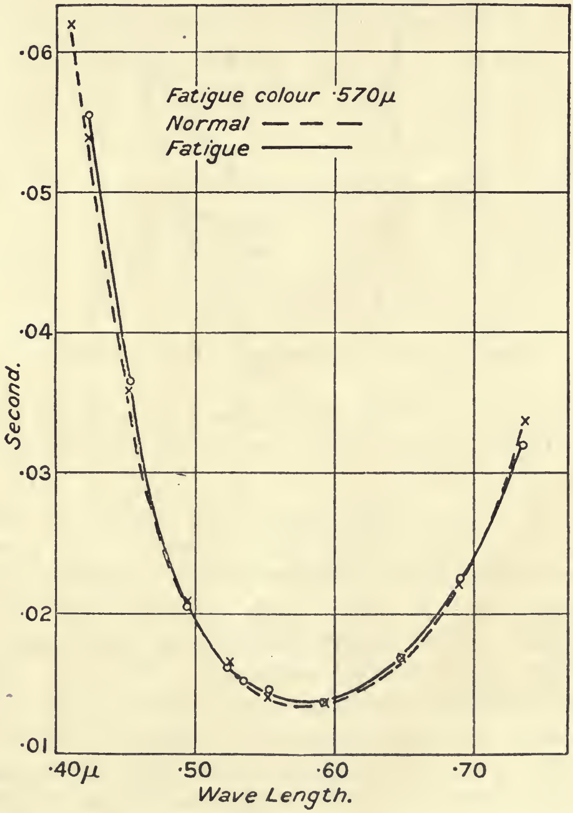


Figure 14. Retina Fatigued with a Transition Color.

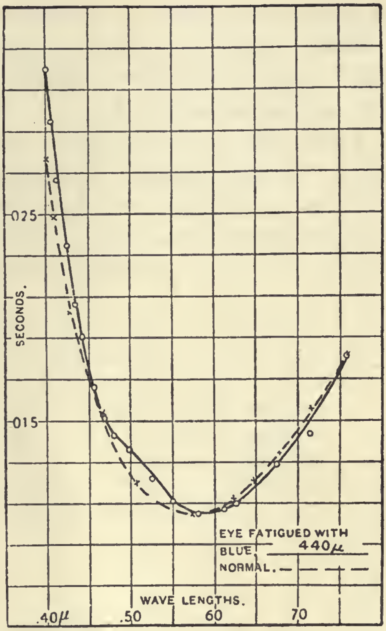


Figure 15. Retina Fatigued with a Deep-blue Color.

to be relied upon in determining the nature of the sensation of yellow than dogmatic assertions based on its mere appearance.

When the green colors .560μ, .540μ and .520μ, were used to fatigue the retina persistency curves of the same type were obtained exhibiting one elevation in the part corresponding to green, the two ends of the spectrum coinciding with the normal. This is clearly shown in that obtained for the wave-length .540μ which is exhibited in Fig. 13. When we compare the double elevation curves of the type of Fig. 11 with those of the single elevation curves of Fig. 13, it is evident that a second transition point must lie between the wave-lengths .577μ and .560μ, since the former of these has two elevations and the latter one. This second transition

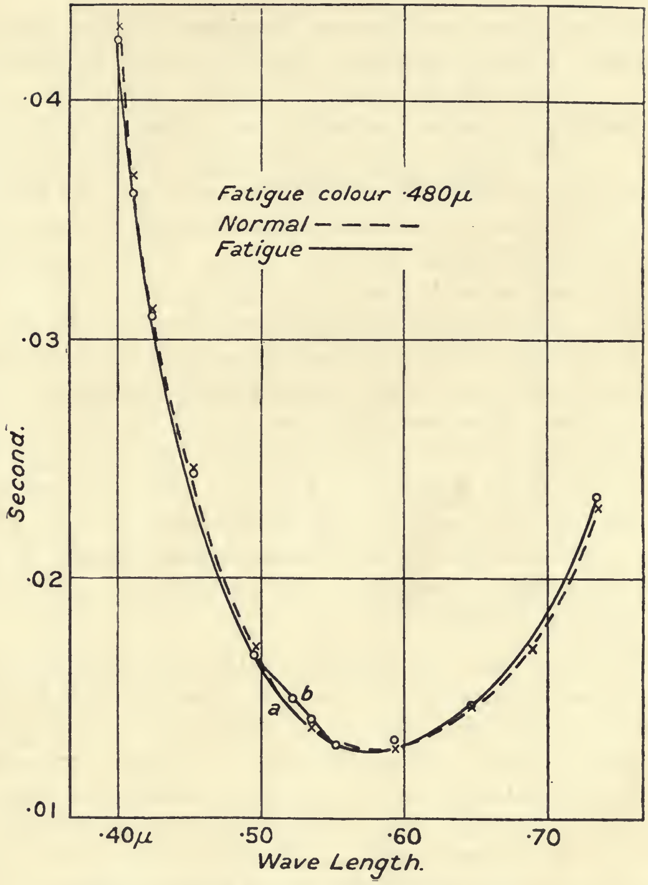


Figure 16. Retina Fatigued with Wave Length 0.480μ

point was found at the wave-length .570μ. When this was used as a fatiguing color the curve shown in Fig. 14 was obtained in which there are no elevations but coincides with the normal throughout its length in exactly the same manner as that for the first transition point shown in Fig. 12.

When the retina is fatigued with the deep blue or indigo color of wave-length .440μ a persistency curve was obtained showing two elevations, one in the green and the other in the violet. These may be seen by inspecting the curves in Fig. 15. It will also be noticed that the part of the curve corresponding to red and orange is not affected in the least degree. If we again compare the single elevation type of curve of Fig. 13 with the double elevation type of Fig. 15, it is at once clear that a third transition point must lie between the wave-lengths .520μ and .440μ. Two intermediate hues were successively used as fatiguing colors, *viz:* .480μ and .460μ. Both curves obtained are reproduced in Fig. 16 and Fig. 17, respectively. It will be seen on inspection that both curves have no elevations in either the green or the violet regions. However, the curve in Fig. 16, for the color .480μ, does show at "b" a slight vestige of the green elevation which is not at all apparent in Fig. 17. We may conclude, therefore, that the spectral region bounded by the wave-lengths .470μ and .460μ is the transition point sought for and I have accordingly designated the wave-length .470μ as the third transition point.

When the retina was fatigued with the violet of wave-length .400μ a persistency curve was obtained with but one elevation in the violet, the rest of the curve coinciding with the normal. This is shown in Fig. 18. Again, comparing this single elevation curve with Fig. 15, which is a curve of the double elevation type, it is clear that a fourth transition point must lie between them. This was found to be at the wave-length .420μ, which when used as the fatiguing color gave the persistency curve shown in Fig. 19. This shows no elevations in any part, but coincides with the normal throughout its length.

We can represent these curves in a different way so as to show them all in one figure. There is evidence to prove that the persistence of vision, or the duration of visual impressions on the retina, is dependent only on the luminosity or brightness of the color, except for very low intensities.

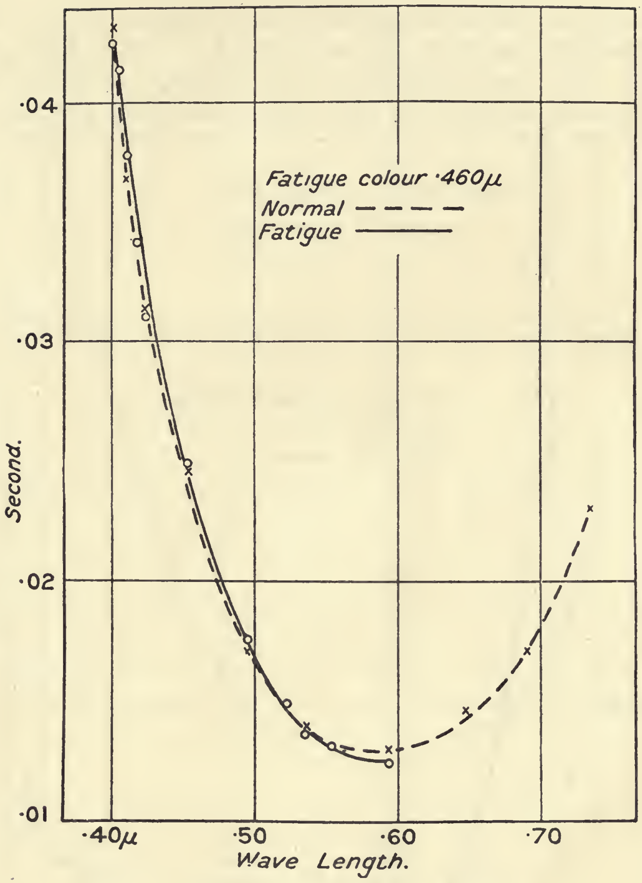


Figure 17. Retina Fatigued with Wave Length 0.460μ

If, therefore, the brightness of all parts of the spectrum were uniform, the persistency curve would be a straight horizontal line instead of the now familiar parabolic form. Reducing, then, the normal curve to such a horizontal straight line, and the fatigue curve in the same proportion, the relation of the two curves will be shown perhaps more clearly, especially in regard to the characteristic elevations. This has been done for the nineteen sets of curves which I have just described and they are all shown in a single figure, *viz:* Fig. 20. The wave-lengths of the fatiguing colors are indicated by the numbers on the right of the diagram and are

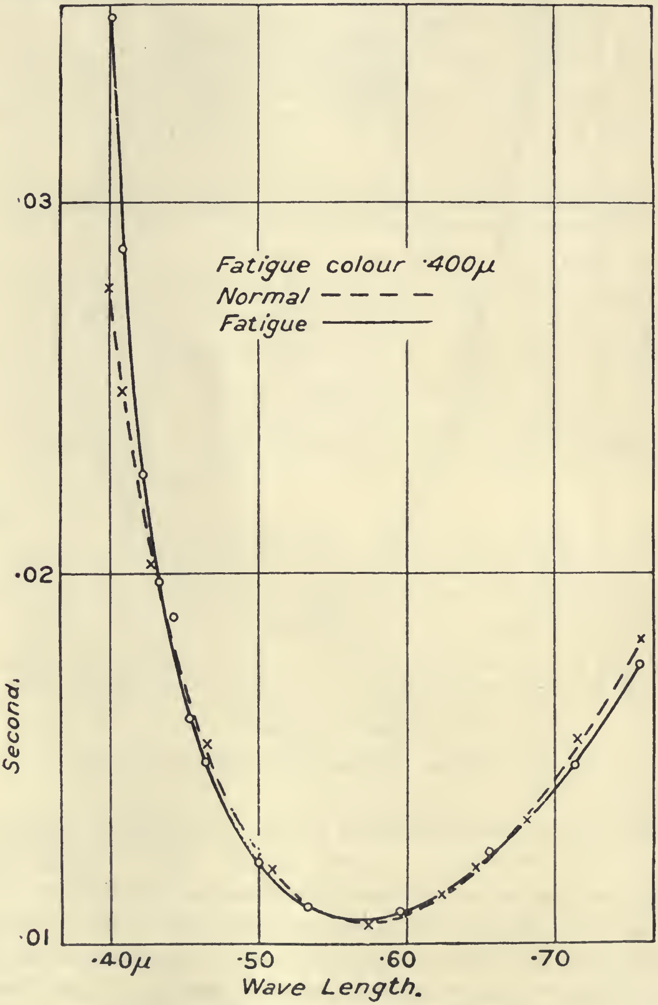


Figure 18. Retina Fatigued with Violet.

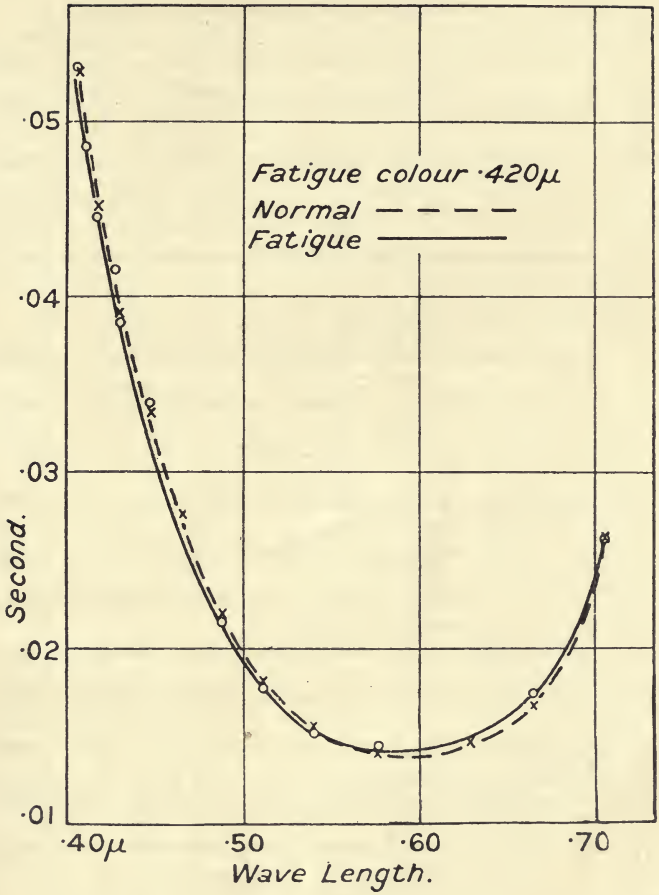


Figure 19. Retina Fatigued with a Transition Color 0.420μ.

also marked by the short vertical lines above the curves. The nature and significance of the double and single elevations, and their relation to the transition points or colors, which are marked T. P., may readily be seen. It will be noticed in particular that the elevations in all the curves occur in the parts corresponding to the red, green and violet

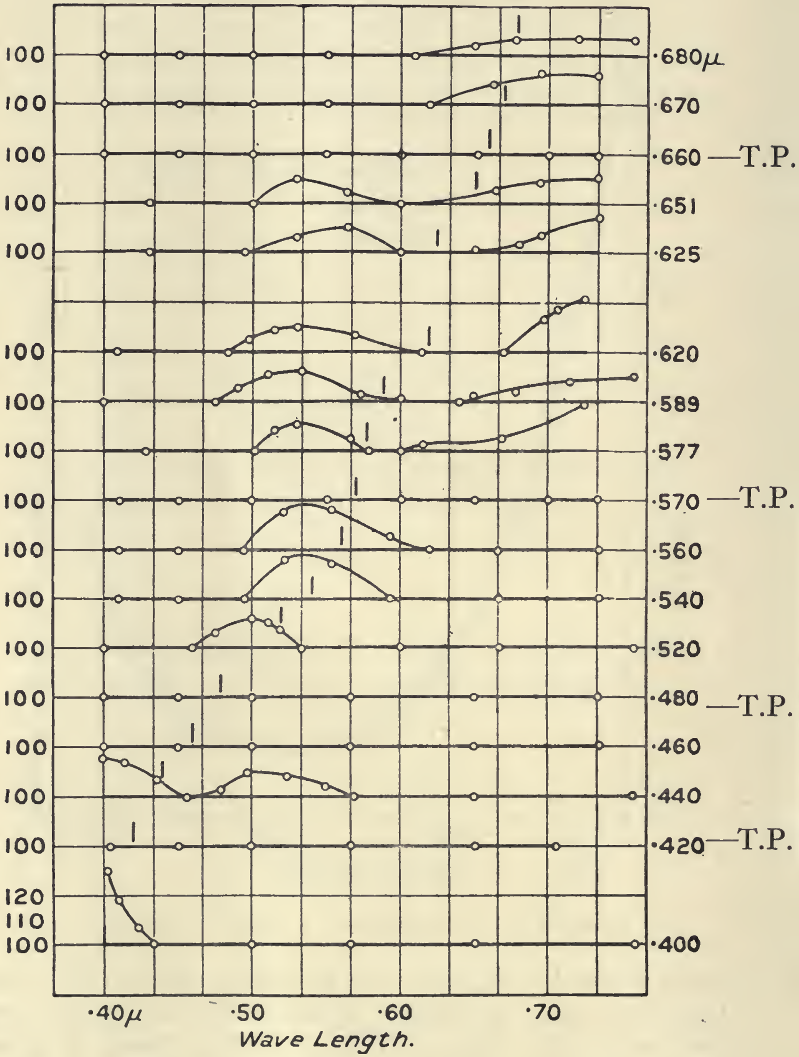


Figure 20. Relationship between the Normal Persistency Curve and the Fatigue Curve.

colors. This fact is strong evidence of the existence of three, and only three, primary sensations corresponding to those colors.

The process of compression may be carried one step further. By taking the mean values of all the elevations we may construct a single composite curve which is shown on an enlarged scale in Fig. 21. The four transition points are indicated by short vertical lines, and fall symmetrically on either side of the two minima of the curve. More conclusive evidence of the reality of the three fundamental color sensations, red, green and violet, could scarcely be desired than is afforded by the three elevations to this curve.

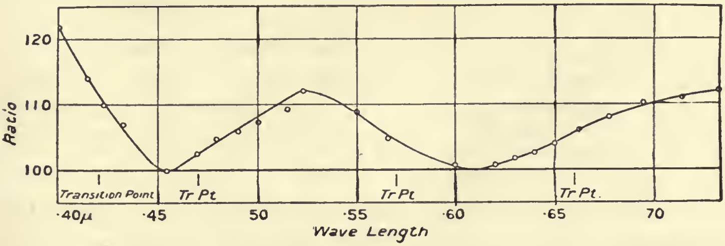


Figure 21. Illustrating Positions of Transition Points.

The general results of these experiments may be represented diagrammatically in Fig. 22. In this diagram the indicated wave-lengths mark the transition points and divide the spectrum into five parts. It is evident that the fundamental red sensation corresponds to some hue between the beginning of the red and the point of transition at .660μ. Similarly the fundamental green sensation is excited by some portion of the spectrum lying between the second and third transition points at the wave-lengths .570μ and .470μ. Finally the third fundamental sensation, which must be violet and not blue, as many color-theorists allege, lies between the fourth point of transition at .420μ and the end of the violet.

For the purpose of comparison, the writer has brought together the exact hues of the primary colors according to several investigators whose experiments were conducted on the basis of the trichromatic theory. With these are included the colors selected by Hering for his theory of color vision, and those determined for the same theory by Baird.

	Red	*Green*	*Blue*
Helmholtz	Carmine-red; not in spectrum.	.56μ to .54μ	Ultramarine Blue
Maxwell	.630μ	.528μ	.457μ
König	Purple-red; just outside spectrum.	.505μ	.470μ
Exner	Red complementary to .494μ (about .66μ)	.508μ	.475μ
Allen	Between end of spectrum and .660μ	.570μ to .470μ	Violet between .420μ and end.

	Red	*Green*	*Yellow*	*Blue*
Hering	Purple-red; non-spectral.	.495μ	.574μ	.471μ
Baird	Purple-red; non-spectral.	.490μ	.570μ	.460μ

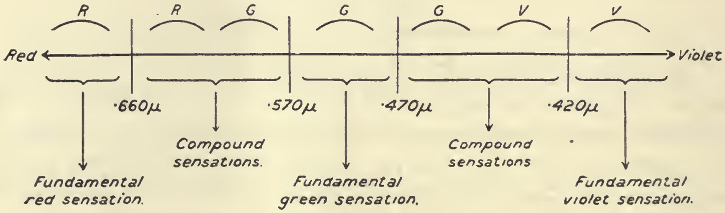

R
R
G
G
G
V
V
Red
Violet
·660μ
·570μ
·470μ
·420μ
Compound sensations.
Compound sensations
Fundamental red sensation.
Fundamental green sensation.
Fundamental violet sensation.

Figure 22. Fundamental and Compound Sensations.

There is no conflict necessarily arising between my own fundamental hues for red and green and those of Helmholtz, Maxwell, König and Exner; there is divergence in the case of violet. But if it is at all justifiable for Helmholtz and the others to differ in their green hues by nearly .06μ, no exception need be taken to my violet determination because it differs from the others by an equal amount.

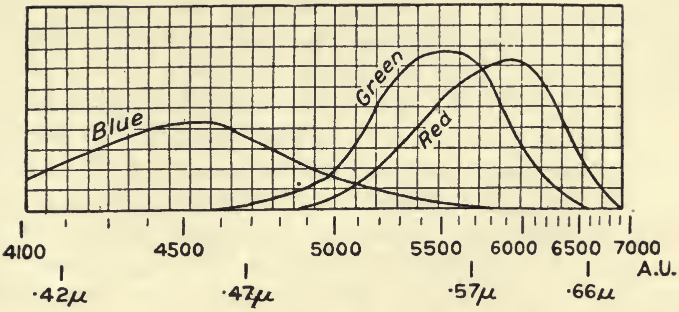


Figure 23. Normal Sensation Curves. (Abney and Watson.)

In endeavoring to connect the transition points with other color-phenomena, I have found specially suggestive the color-sensation curves of Abney and Watson, Fig. 23, and of König and Dieterici, Fig. 24. On each of these figures I have indicated the transition points by short vertical lines with wave-lengths attached. The meaning of these sensation curves is that the sensation excited by any given wave-length of the spectrum is really made up of a combination of red, green, and blue or violet sensations in proportion to the ordinates of the curves at the given wave-length.

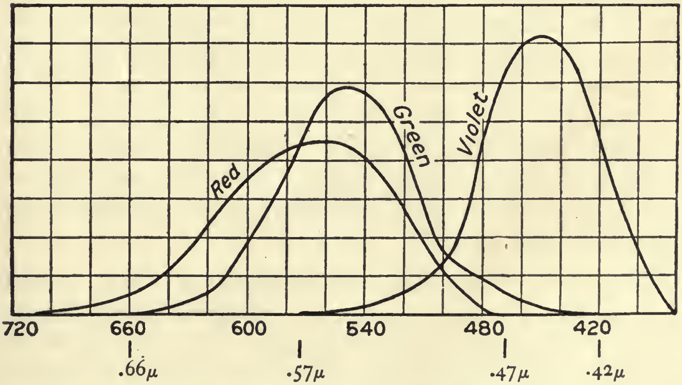


Figure 24. Sensation Curves. (König and Dieterici.)

In the curves of Abney and Watson the transition points $.660_{\mu}$ and $.470_{\mu}$ are practically at the ends of the sensation curve for green; and the other transition points at $.420_{\mu}$ and $.570_{\mu}$ are near the ends of the sensation curve for blue. The transition point at $.570_{\mu}$ is also very close to the intersection of the green and red sensation curves. The transition point at $.420_{\mu}$ is shown by the curves to be practically outside the influence of the red and green sensations, and hence may be regarded as a region of a single pure color sensation. Similarly, the spectral region from the transition point $.660_{\mu}$ to the end of the spectrum is pure red free from the influence of the other two sensations.

The sensation curves of König and Dieterici, Fig. 24, show some differences. The ends of the green sensation curve are the transition points $.660_{\mu}$ and $.420_{\mu}$, while the transition point $.470_{\mu}$ is still the more refrangible end of the sensation curve for red. The transition point $.570_{\mu}$ marks one end of the sensation curve for violet. It will be noticed that the regions between the transition points $.660_{\mu}$ and $.420_{\mu}$ and the respective ends of the spectrum are, as before, characterized by purity and simplicity of color sensation. The transition point $.570_{\mu}$ is again at the intersection of the red and green sensation curves, that is, where the two sensations balance the influence of each other, without sufficient of the third sensation to make itself perceptible. In both figures one can see reasons why the regions between $.420_{\mu}$ and $.470_{\mu}$, and between $.570_{\mu}$ and $.660_{\mu}$ should be characterized by compound sensations. But it is difficult to understand why the exceedingly complex region between $.470_{\mu}$ and $.570_{\mu}$ should exhibit, as it does, persistency curves with only one elevation in the green.

The general conclusions regarding the color sensations which we have now reached are greatly strengthened by the study of natural color-blindness. Since we have proved the fundamental sensations to be red, green and violet, we may anticipate the possible types of color-blindness. In general there may be: three types in which *one* sensation is missing; three types in which *two* sensations are missing, and one type in which *three* sensations are missing; that is, there are seven possible types of color-blindness. We may represent them as follows:

Red-blindness.
Green-blindness.
Violet-blindness.
Red-Green-blindness.
Red-Violet-blindness.
Green-Violet-blindness.
Red-Green-Violet-blindness.

Some years ago I made a close study of color-blindness and determined the persistency curves of about twenty-six cases. Among them I found no less than six out of the seven possible types, the only type I did not discover being violet-blindness. These curves are all reproduced in Plates I, II and III, and the classes to which the individual curves belong are indicated on the curves in accordance with the following classification.

Class I	Red-blindness.
Class II	Green-blindness.
Class III Class IV	Red-Green blindness—Two varieties.
Class V	Red-Violet blindness.
Class VI	Green-Violet blindness.
Class VII	Red-Green-Violet-blindness; or total color blindness.

Since Classes III and IV are really two subdivisions of the same general type, the seven classes include only six types. These persistency curves for color-blindness bear a remarkable resemblance to those which we have studied for retinal fatigue, which is thus seen to be analogous to artificial or induced color-blindness.

As far as we may conclude from these cases the most common types of color-blindness are: red-blindness, red-green blindness and red-violet blindness, which together comprise

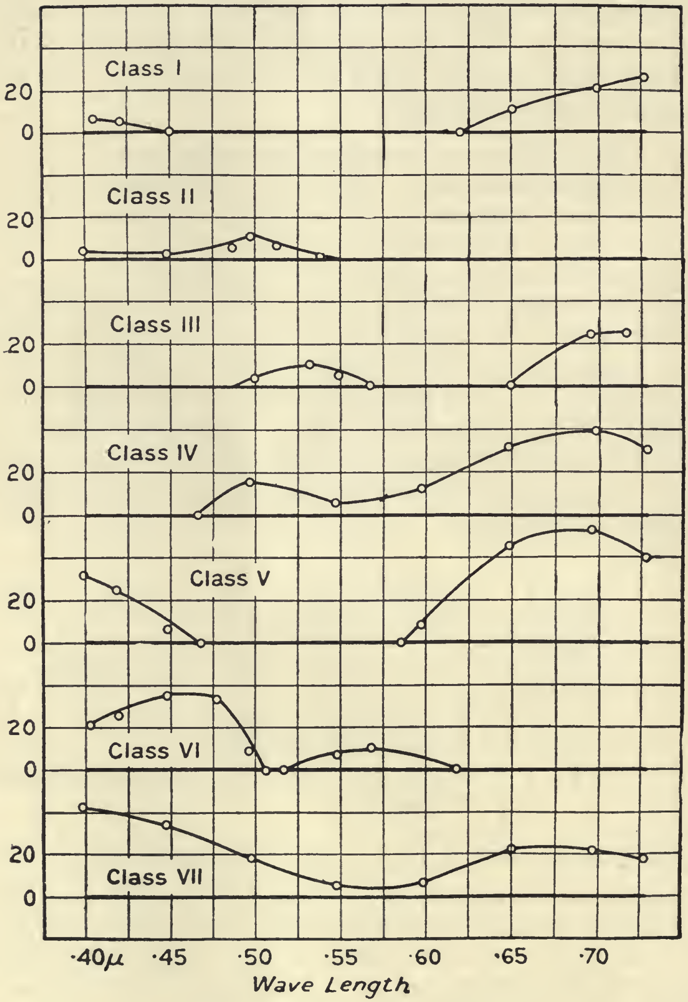


Figure 25. Departures of Persistency Curves of Color-blind Persons from the Normal Persistency Curve.

twenty out of the twenty-six cases studied. Some of the other types are evidently distinctly rare.

Typical examples of these curves are shown also on the single diagram plan in Fig. 25, which exhibits the characteristic elevations in the clearest manner. It will be of advantage to compare this figure with the curves in Fig. 20 which is described above. These curves for color-blindness confirm in the strongest and clearest manner the conclusions already reached from the experiments on normal eye regarding the number and designation of the fundamental color sensation.

One further problen in color vision may be fittingly referred to in concluding this paper. On one occasion I fatigued

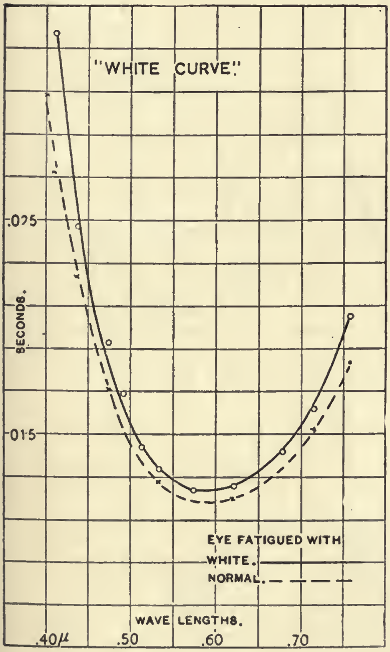


Figure 26. Persistency Curve after Fatiguing with White Light.

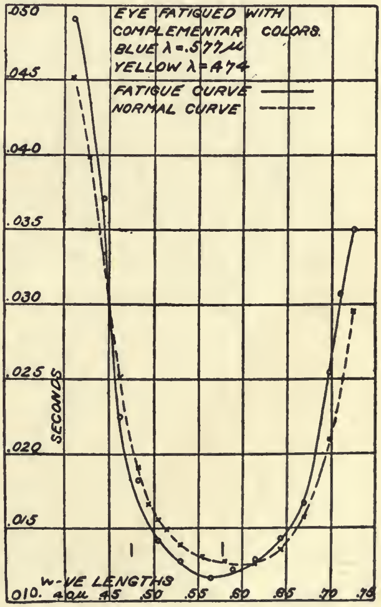


Figure 27. Persistency Curve of the Eye Fatigued with Complementary Colors, Blue and Yellow.

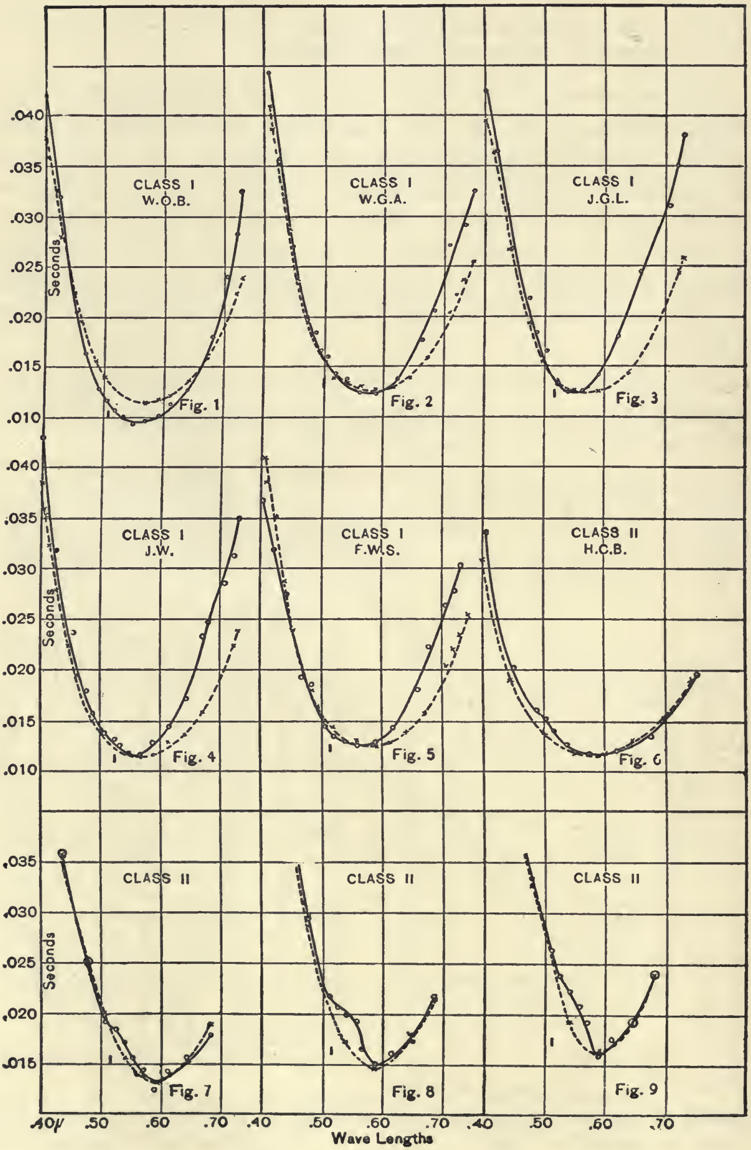


Plate I. Classes of Persistency Curves of Color-blindness.

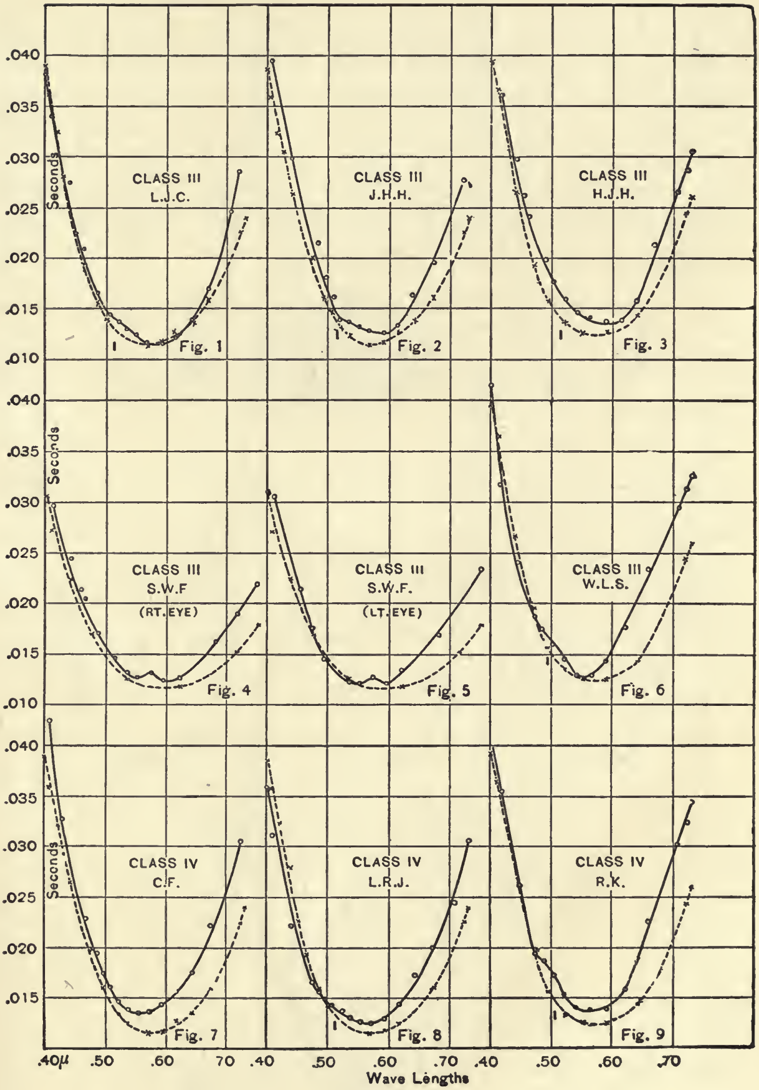


Plate II. Classes of Persistency Curves of Color-blindness.

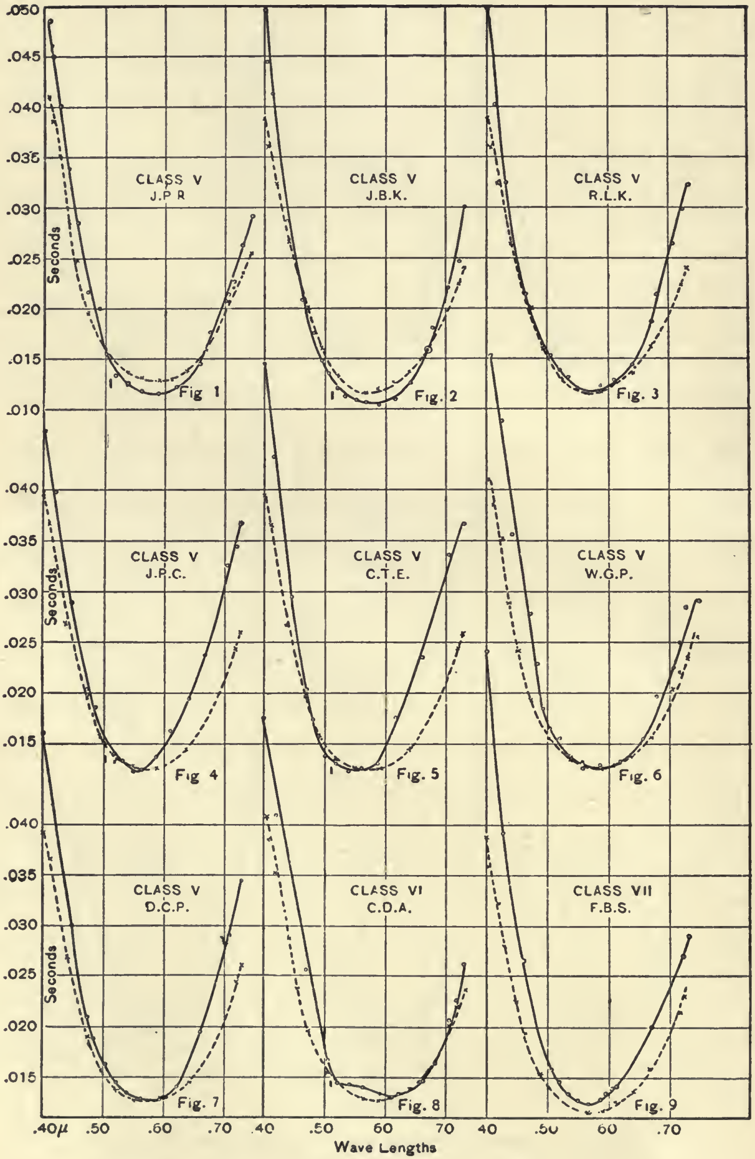


Plate III. Classes of Persistency Curves of Color-blindness.

my eye with white light from an electric arc and obtained the persistency curve shown in Fig. 26. In this, the whole fatigue curve is elevated above the normal. This it will be observed is exactly like the one obtained by a totally color-blind person and shown in Plate III, Fig. 9, Class VII. As white light, indistinguishable from ordinary white, may be obtained by mixing two complementary colored lights, observations of the persistence of vision were made after fatiguing the retina with proper combinations of colors.

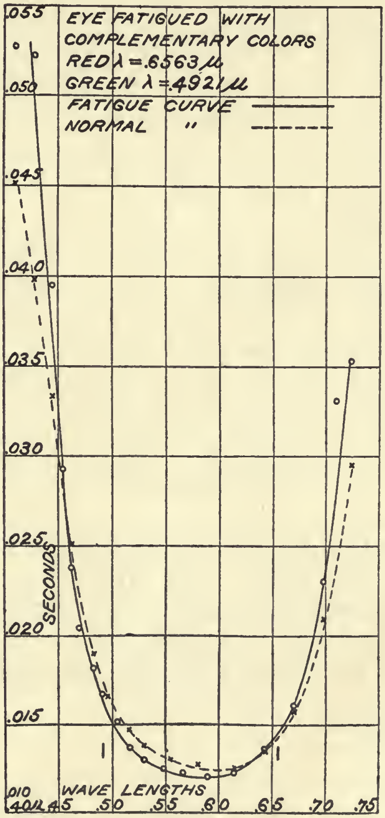


Figure 28. Persistency Curve of the Eye
Fatigued with Complementary Colors,
Red and Green.

Two overlapping spectra were formed in a color mixing spectrometer and the selected complementaries combined in a shutter eyepiece. The intensities of the two component colors were adjusted so as to give a pure white light. The first pair of complementaries used were yellow .577μ and blue .474μ as determined by Von Kries. The second pair were red .656μ and green .492μ as determined by Helmholtz. The persistency curve for the former pair is shown in Fig. 27 and that for the latter in Fig. 28.

On comparing the figures both curves are seen to be essentially the same and also to differ greatly from the white fatigue curve of Fig. 26. Instead of the whole of the complementary color curves being elevated above the normal, the part corresponding to green is actually depressed below the normal. They bear in fact a close resemblance to the curves obtained for the cases of red-violet blindness shown in Plate III, Class V.

The effect on the retina of white light of the comparatively few wave-lengths comprised in the complementary colors must of necessity be different from that of the complex mixture of waves forming the white light from an electric arc. The psychological effect of the two kinds of white light is precisely the same; yet measurements of the persistence of vision are capable of showing in a most striking manner the differences in the physiological effects of the two lights on the retina.

This is the extent to which my researches on color vision have at present carried me. It is evident that much interesting information regarding the retinal processes excited by the vision of colors is yet awaiting discovery, and no doubt this method will be of great service to that end.

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Editorials

Bashful Books Worth Knowing

IT goes almost without saying—and yet we have to say it —that all of us know bashful people: people of good, homely yet wholesome appearance and clothed in dress of hodden-grey, who bask not in the limelight but modestly go about their businesses and day's labors with few words and little ado. They do not thrust themselves forward nor try to impress us with their wisdom. Yet their minds run true and their words ring clear when they are tested. Like the still waters, they run deep. Their acquaintance is not made in a few hours' time, while a knowledge of their true worth is acquired only after years of association. When we succeed in lifting the "bushel" there we find the "light." And, just by way of contrast, there are those who are like the tinkling brass—it is all in the tinkle. For it takes all kinds of people to make a world.

And some books are like some people—bashful to the extreme, unprepossessing in their outer appearance, dry in apparent form and apparent substance, but with years of association they become guides unto the pathways and lamps unto the feet of their possessors.

Writers and publishers of present day fiction surely cannot complain that their products are not eagerly seized and devoured by an ever ready public. And it is well that such is so, for everyone of us, from the youngest child to the oldest person still clinging to that which we call life, needs relaxation and a good story is a splendid tonic. But alas and alack! The most trivial romance that bears the imprint of some reputable publisher is reviewed in the newspapers from one end of the country to the other, while so-called fashionable clubs discuss by day and fickle youth devour by night the latest and best-sellers. The best-seller is not a bashful book.

But there is a fair sized class of really useful books. These are seldom mentioned in the public press and none too often in the professional sheet, and of their existence only the initiated know. These books must be ferreted out by years of toil—they are the bashful books that pertain to a man's or woman's vocation or life's work.

Surely we have not missed our guess when we gamble that every reader of these words is aware of our reference to the Five Foot Book-Shelf. Yes, indeed, some of the best of the Bashful Books, so picked and grouped that even the "fastest of the fast" of those who run the merry chase of modern life may still perchance become acquainted with some of the really worth-while literature of the world.

And in many ways the idea of a five foot book-shelf has appealed to us, not because it is five feet in length but because of the fact that to "him who hath shall be given"—as true in the world of books as in the world of finance—and sooner or later the five-foot shelf of books will have doubled and then tripled. True it is that to be the master of a few books, well selected, is to be the peer of him who has a smattering of a great many tomes, but the probability is that he or she who makes the acquaintanceship of a few bashful books will add to this family with the oncoming of the years.

It is a pitiable condition in which we find so many professional men—often men of the best of trainings and men of the best of prospects. We go into the office, we enter the *sanctum sanctorum*, we pry around, we delve and we dig and alas! We find no shelf of well-thumbed, much-studied and perused bashful books. We find the professional man so engrossed in the duties of his profession, be that what it may, or else so side-tracked and taken up with outside interests, that he has failed to provide himself with the best of the world's thought and experience in his chosen line. Or perchance, having possessed himself of these, he takes satisfaction in looking at their titles and cajoles himself into believing that he can make these bashful books his intimate friends. No indeed: there is but one way to live with books and that is, as Bacon said, to "read, mark and inwardly digest." And as never before do we fear it is true today that the professional man is failing to spend a *reasonable* number of his hours with his bashful books. And each must interpret for himself the meaning of that word *reasonable.*

The bashful books, like the still waters, run deep. They are the books that point the way: they are the books that should be parts of ourselves. They are the books that make us think, that stimulate our mental processes, that help us get out of the ruts of relegated notions, and that open up to us the vistas of undreamed of and unsung things.

Color and Mental Efficiency

THE problem of what may be termed the higher psychology of color can be said to comprise two divisions. One of these is the problem of color preference, while the other has to do with the influence of color on mental efficiency. The affective tone, *i.e.* the condition of pleasant or unpleasant effects of color experience or the emotional effect, may enter both of these factors. Much has been said and written on these topics, but lack of scientific method and absence of agreement characterize the whole matter. It is doubtless true that in some historic period or other, nearly every color has been preferred by one group of individuals or another. But there seems to be quite general agreement that brightness and redness have stimulating effects.

Quite recently, Pressey of the Harvard Psychological Laboratory has carried on some experiments on the influence of color upon mental and motor efficiency. His results confirm the effective neutrality or equivalence of colors when considered as isolated factors of experience. His work consisted in studying the effects of single colors, spread uniformly over the visual surroundings of the subject, upon the mental activities. Primary red, green and blue of equal saturations were used. The person tested sat at a table covered with white unglazed paper which was flooded with light of the desired color through the use of suitable screens.

Stefanescu-Guanga, at Leipzig, believed that his experiments showed a marked influence of color upon the respiration and heart action but recent experiments show that there are no consistent effects of this character.

The effects of colored light upon muscular facility were tested by the person under examination tapping at a "comfortable" rate with the finger during one-minute periods. Pressey experimented with five subjects and found no effect of color upon the rate of tapping, while significant increases in the tapping rate were obtained by increasing the brightness of the light. Another test applied consisted in requiring the subject to register a definite pressure with the hand upon a postal scale. The results were negative for both color and for brightness. And again, closer contact with the affective experiences of a subject was obtained in a series of tests made upon the effects of color upon the pleasantness of "touch substances." Such touch substances were simple squares of materials of different textures: the person under test scaling his estimate of pleasantness or its converse when these test objects were illuminated by different lights. And again the results were negative.

Tests upon mental efficiency as effected by colored illumination in such processes as that of multiplication were made. Increased brightness increased the rate of work but no specific effect due to color could be found.

The so called "free association" test was employed. In this test the experimenter speaks a single word—such as father—and the subject under examination replies as quickly as possible with the first word which comes to his mind which is associated with the word given by the experimenter. The time required to think of this associated term is recorded by some form of chronograph. This recall of ideas by association is one of the fundamentals of mental action; it is a very fruitful test in mental efficiency investigations. Another method is the determination of the rate at which the subject memorizes nonsense syllables. The latest tests at the Harvard laboratory indicate that there is no influence either of color or brightness.

"Continuous choice reaction" tests as carried out by Pressey showed that there was no appreciable influence of color or of brightness. In the ordinary choice reaction experiment the subject reacts in a certain manner if a certain stimulus is presented and in a different way if a certain other stimulus is presented. The muscular response is definite with reference to the stimulus applied. The method is ordinarily followed of applying these choice-reaction tests one after the other as rapidly as the subject responds; the number of correct reactions in a given time determines the result of the test.

Numerous sets of experiments involving introspective reports concerning the affective value of colors show that there is little or no consistency from individual to individual and that it varies with the individual from day to day. As a general rule, red has been found to be more exciting than indifferent and bright illuminations are generally preferred to dim. In other cases the reverse is true.

The general conclusion to which we are drawn from such work as that of Dr. Pressey, carried out with a couple dozen subjects over a period of three years, is that the higher psychological influence of color in illumination is of very minor importance. Certainly, however, these laboratory tests cannot dispose of the proposition that the use of color in lighting has no practical influence upon human happiness or efficiency. It is more than probable that numerous individuals will still "see red" and want to fight and there is but little doubt that a constant living under blue lights may give one the "blues." Perhaps it isn't so—it is so only because we think it is so—because we have been taught that it is so! For has not community life and individual experience taught us that red is associated with danger, blood and fire?

None of the tests we have mentioned in the foregoing paragraphs involve visual tests such as visual acuity. Because of the chromatic aberration of the eye we know that monochromatic light gives a better defined retinal image than does white light. Likewise, the eye is quite accurately corrected for achromatism at about the mid-region of the spectrum—the yellow-green, or region of maximum visibility—and that it is very imperfect in this respect in the end regions, the red and the blue. In practical lighting we employ a white light source, *i.e.* one of wide spectral range, hence the acuity factor and any efficiency tests involving visual acts would demand the use of the yellow-green. Luminous efficiency criteria demand similar conditions.

The state of the nervous system and the conditions of fatigue and of overwork may be important factors in any individual cases tested for the effect of color on human efficiency. Psychopathic cases are not rare in which the viewing of certain colors is sufficient to produce hysterical reactions and even to arouse emotions of fear. Hence the only conclusions which can be drawn from numerous experiments are of the nature of generalizations as applicable to the *average*. But it is said that Americans are, as a nation, a set of high-strung creatures and that they are prone to neurasthenia—whatever that term may mean to the reader, since no two seem to mean the same thing when they speak or write the word. And we know that the nervous derangements, re-arrangements of functioning, etc. etc. occur in large measure in middle life. We are, therefore, not so positive that fifty good hard-working office and shop men and women of one of our modern cities, having passed the ages of thirty to forty-five or thereabouts, would be so impervious in their reactions to color illumination. We do not say that they would or would not, but we wish that somebody would inaugurate various experiments on those who work day in and day out and experience the pleasures and sorrows of an average life, and pass up for the time being the young, irresponsible and care-free college boy and girl. In other words, who can say that the lighting conditions of the home, of the office and of the factory do not produce marked effects, not necessarily on our mental efficiencies but upon our whole nervous selves? Who can at present say that working day in and day out under red light or under the blue of the mercury arc does not produce slow changing but ultimately appreciable effects upon the efficiency of individuals thus situated?

The Reactions of the Retina to Light

P. G. Nutting, Ph.D.

VISION is accomplished through the influence of certain kinds of radiation upon the retina. The various responses of the retina to radiation correspond with those of a number of different kinds of physical instruments, each giving its particular kind of scale reading and each scale reading representing a certain sensibility or ratio of increment of scale reading to increment of stimulus producing it. The practical usefulness of our eyes is a matter of the sensibility and range of response of our retinas to the stimulus of light in its various forms.

The quantitative study of the response of the retina to light practically began with the work of A. König twenty-five years ago. Subsequent advances in our knowledge of radiation made much more precise work possible and during the past fifteen years the investigation of the various responses of the retina to radiation has been vigorously prosecuted. At the present time, preliminary surveys of all the more important fields have been made but much remains to be done in determining the properties of the average eye by observations on large numbers of subjects and in working out the numerous applications of this information to problems in photometry, illumination, colorimetry, etc., and to the design of optical instruments. This summary of our present knowledge of the subject covers: I. The Visibility of Radiation, II. Intensity and Contrast Sensibility, III. Chromatic Sensibility, IV. Rates of Adaptation and V. Absolute Sensibility.

The Visibility of Radiation

The amount of radiant energy (measured in watts) necessary to produce a fixed luminous sensation of brightness (in lumens or lamberts), varies enormously with the wave-length of the radiation. It is least in the mid-green, about .0015 watt per lumen, at a wave-length of about 556 millimicrons. The ratio is ten times as large as in the blue-green on the one hand and in the red on the other hand and it is ten thousand times as large at 556 as in the extreme violet (wave-length 400) and extreme red (750). An eye well dark-adapted perceives a light sensation from radiation at least as far out as 330 in the ultra violet and 900 in the extreme red if sufficiently intense.

Various methods have been employed by numerous observers in determining the relative visibility of radiation. A number of the earlier observers[1] measured the relative energies necessary to produce the threshold of light sensation. Another group[2] of observers used as a fixed standard of luminosity, that just sufficient to permit the correct reading of tables of numbers. König[3] used a white comparison field of fixed known brightness, that brightness varying in nine different sets of observations from the threshold of vision up to about 600 meter candles. Later observers[4] avoided the direct comparison of white with colored fields by using the flicker photometer for this purpose. Allen[5] obtains a visibility curve with no comparison field at all by simply noting the critical frequencies at which flicker just disappears at the various wave-lengths. Hyde[6] has recently obtained excellent visibility curves by the step-by-step method, the brightness of each part of the spectrum being compared not with a white standard but with a neighboring portion of the spectrum. The relative merits of these various methods have yet to be carefully investigated. There has been no lack of normal subjects; Ives had 19; Nutting, 21; Hyde, 29 and Coblentz and Emerson, 125. The spectral energy of the acetylene flame, upon which most of the best data are based, is fairly well known though several times revised. Improvements are to be looked for in the use of carefully studied sources, larger spectral apparatus of higher dispersion and a carefully chosen method of observation and of reduction of observations. All the modern data refer to visibility at moderate and high intensities (cone vision?). König's investigation of visibility at low intensities (rod vision?) should be repeated with modern apparatus and methods.

König's early data on relative visibility at various intensities, as reduced by the writer[7], are given in the following table. There exists considerable uncertainty in these data due to uncertainties in (1) the correction for the dispersion in the prism employed and in (2) the spectral energy of the source (a gas flame). This latter determination was made for König by Langley in Washington on a somewhat similar gas flame.

König's Data on Visibility

Intensities (m.c./mm² pupil) Ratio to Preceding Step	0.00024 (threshold)	.00225 9.38	.0360 16	.575 16	2.30 4	9.22 4	36.9 4	147.6 4	590.4 4
Wave-Length	Visibility								
430	.081	.093	.127	.128	.114	.114	...	...	...
450	.33	.30	.29	.31	.23	.175	16	...	...
470	.63	.59	.54	.58	.51	.29	.26	.23	...
490	.96	(.89)	(.76)	(.89)	(.83)	.50	.45	.38	.35
505	1.00	1.00	1.00	1.00	.99	(.76)	.66	.61	.54
520	.88	.86	.86	.94	.99	(.85)	.85	.85	.82
535	.61	.62	.63	.72	.91	(.98)	.98	.99	.98
555	.26	.30	.34	.41	.62	.84	.93	.97	.98
575	.074	.102	.122	.168	(.39)	(.63)	(.76)	(.82)	(.84)
590	.025	.034	.054	.091	.27	.49	.61	.68	.69
605	.008	.012	.024	.056	.173	.35	(.45)	.54	.55
625	.004	.004	.011	.027	.098	.20	.27	.35	.35
650	.000	.000	.003	.007	.025	.060	.085	.122	.133
670	.000	.000	.001	.002	.007	.017	.025	.030	.030
max	.503	.504	.504	.508	.513	.530	.541	.543	.544

The shift of the visibility curve toward longer wave-lengths with increasing intensities (the basis of the Purkinje effect) is clearly shown. The threshold visibility curve is reproduced in the accompanying figure.

In the following table are summarized the best data on the visibility of radiation of moderate and high intensities (cone vision). Absolute values of visibility or ratio of light to energy, in lumens per watt, are given in the final column. These are calculated from the visibilities on the basis of a mechanical equivalent of 0.0015 watt per lumen or a luminous equivalent of 667 lumens per watt for maximum visibility (at wave-length 556).

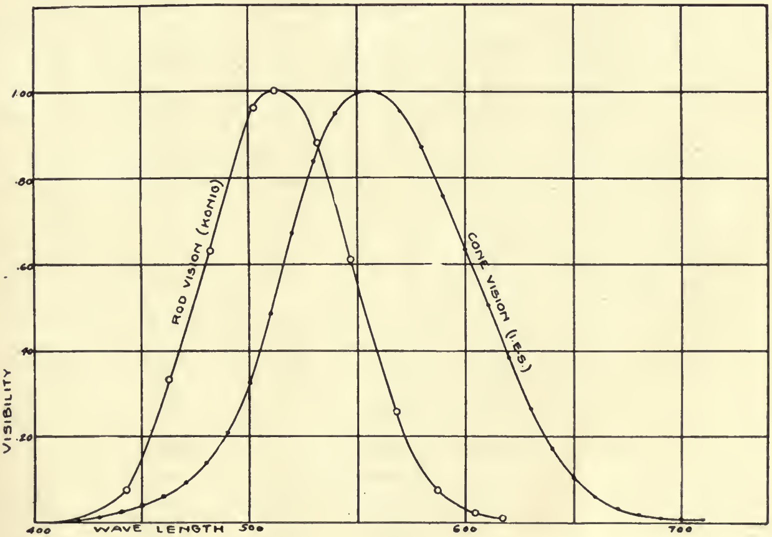

Figure 1. Visibility of Radiation.

DATA ON VISIBILITY

(Ordinary Cone Vision)

Wave-Lengths	Ives and Kingsbury	Nutting	Coblentz, Emerson	Hyde, Cady, Forsythe	Adopted Mean I. E. S.	Absolute Visibility
400	0.0003	0.0021	0.006	0.00009	0.0004	0.27
10	.001	.0036	.011	.00062	.0012	0.80
20	.005	.0065	.015	.0041	.0040	2.7
30	.012	.0115	.020	.0115	.0116	7.72
40	.024	.022	.029	.022	.023	15.3
450	0.040	0.038	0.041	0.036	0.038	25.3
60	.060	.064	.058	.055	.060	40.0
70	.090	.101	.086	.087	.091	60.7
80	.137	.149	.128	.138	.139	92.6
90	.211	.215	.194	.216	.208	139
500	0.318	0.314	0.320	0.328	0.323	216
10	.473	.456	.503	.515	.484	322
20	.637	.646	.710	.698	.670	446
30	.801	.815	.862	.847	.836	557
40	.915	.925	.954	.968	.942	629
550	0.988	0.986	0.997	0.996	0.993	662
60	.996	.995	.998	.995	.996	663
70	.947	.949	.968	.944	.952	641
80	.859	.871	.898	.855	.870	580
90	.758	.762	.800	.735	.757	502
600	0.653	0.634	0.685	0.600	0.631	421
10	.534	.498	.555	.464	.503	336
20	.396	.368	.425	.341	.380	253
30	.283	.268	.305	.238	.262	175
40	.183	.166	.195	.154	.170	113
650	0.110	0.105	0.114	0.094	0.103	68.8
60	.068	.058	.062	.051	.059	39.3
70	.039	.032	.032	.026	.030	20.0
80	.026	.016	.0162	.0125	.016	10.7
90	.014	.0081	.0080	.0062	.0081	5.4
700	0.007	0.0036	0.0038	0.0031	0.0041	2.7
10			.00190	.0015	.0021	1.4
20			.00092	.00075	.0010	0.67
30			.00045	.00036	.00052	0.35
40			.00024	.00018	.00025	0.17
750			0.00015	0.00009	0.00012	0.08
60				.00005	.00006	0.04
Wave-Length of Maximum	556	556	557	556	556	

The visibility curve is roughly in the form of the well known probability curve but slightly steeper on the violet side. It may be represented by the probability curve, but for mathematical purposes (converting radiant energy into light), it is more convenient to use the form

$$V = V_m \, R^a \, e^a \, (1 - R) \text{ or}$$
$$\log (V/V_m) = a \, (\log R + 1 - R)$$

in which $R = 556/\text{wave-length}$, and $V_m = 667$ lumens/watt.

The absolute value of the visibility constant V_m in lumens per watt has been determined by a number of investigators. The method used is to measure some convenient illumination both as light and as energy. The monochromatic green mercury line 546.1 has been used, also the nearly white light from an acetylene flame or incandescent lamp (integrated) and filtered white light. Even the best determinations are not in very good agreement, ranging from 625 to 667 lumens per watt. The corresponding value, the ratio of the lumen to the watt for rod vision, is yet to be determined.

A knowledge of the visibility of radiation as determined by the reaction of the average normal fovea to radiation is of the utmost importance in many branches of optics and illuminating engineering. The data given above are essential in reducing radiant energy to light for example and in calculating the brightness of a heated body at a known temperature. It would be quite feasible to establish a standard of light in terms of radiant energy through similar data more accurately determined. In optical pyrometry and other problems it is necessary to calculate by means of the visibility curve the amount of light past a given light filter. It is to be hoped that the problems connected with the precise determination of visibility may be attacked even more vigorously in the future.

II. Color Sensibility

The human retina is sensitive not only to differences in brightness but to differences in the quality of that brightness, due essentially to the composition of the radiant energy reaching it. The differences in quality of the radiant energy are those of wave-frequency or wave-length. In the preceding paragraphs have been discussed the range of wave-lengths to which the eye is sensitive. Color discrimination depends upon the ability to distinguish between lights of different dominant wave-lengths. It is, of course, impossible to set down the precise sensation corresponding to each wave-length, but we can readily determine sensibility to differences in wave-length and integrate this sensibility into a continuous color scale. Finally the pure hue may be mixed with either white or black and here again sensibility to differences may be observed and integrated into scales of tint or shade. Any one color may be specified by three and but three co-ordinates, namely (1) wave-length of *dominent hue*, (2) *saturation* as regards admixture of white, and (3) *intensity* represented in the case of self-luminous bodies by emissivity and in other bodies by either reflecting or transmitted power of light.

Sensibility to differences in wave-length may be readily determined by means of a modified simple spectrometer having two collimators separately movable. While one is held fixed the other is moved toward either longer or shorter wave-lengths (usually each alternately) until the color difference is just noticeable. Then the movable one is held fixed while the other is loosened and moved to give a just noticeable difference in color. A good bright spectrum stepped off in this way gives from about 130 to 180 distinctly different pure hues between the red and violet, while from violet back to red through the purples and magentas there are about 20 additional steps as determined by their complementaries in the green. The variation of color sensation with wave-length is by no means uniform as may be seen by a glance at a spectrum. In two regions, namely in the blue-green and in the yellow, hue changes very rapidly with wave-length, while in the middle of the green and red, hue changes very slowly with wave-length. Beside these two pronounced maxima of sensibility at wave-lengths of about 490 (blue-green) and 585 (yellow), there are lesser maxima at about 637 in the red and 440 in the blue-violet.

The first reliable data of this nature was published by Steindler[8] in 1906 and reduced and published by the writer[9]. Steindler had 12 subjects, all with normal color vision. Curves were averaged not by taking the average sensibility at each wave-length, but by finding the average wave-length of each maximum and minimum of sensibility, since averaging the sensibilities would have given a mean curve flatter than any individual curve.

More recently this work has been repeated by L. A. Jones and the writer, using several forms of special spectrometer for the purpose. These data are in very close agreement with those of Steindler taken 10 years previously in Vienna. Mr. Jones further made determinations[10] with his left eye as well as right eye, knowing that the two eyes were practically the same in color sensibility. These data are summarized in the following table and figure.

Hue Sensibility

	A		B		C		D		E		F	
	λ	dλ	λ	dλ	λ	dλ	λ	dλ	λ	dλ	λ	dλ
At λ = 660	660	6.0	660	5.2	660	5.0	660	...	660	5.4	660	6.0
First Minimum	635	2.8	638	2.4	637	2.4	635	3.1	637	2.5	637	3.0
First Maximum	622	3.4	628	3.5	623	3.2	620	3.7	624	3.4	621	3.7
Second Minimum	584	1.4	585	1.2	586	1.1	584	1.4	585	1.2	580	1.4
Second Maximum	538	3.5	540	3.3	537	3.2	538	3.0	538	3.3	535	3.3
Third Minimum	496	1.2	490	1.1	495	1.1	496	1.0	494	1.1	492	1.3
Third Maximum	462	2.3	465	2.4	464	2.5	465	1.9	464	2.4	458	3.1
Fourth Minimum	442	1.8	443	1.8	445	1.8	454	1.5	443	1.8	440	2.4
At λ = 410	410	4.0	410	4.6	410	4.0	410	5.0	410	4.2	440	5.5

Column A ..... 1st determination with the right eye (discontinuous)
" B ..... 2nd " " " " "
" C ..... 3rd " " " " (continuous)
" D ..... 1st " " left " (discontinuous)
" E .....Mean values of A, B and C.
" F ..... " " from Steindler data (12 subjects)

The hue sensibility is taken as the reciprocal of the just noticeable difference in wave-length. The hue scale is the integral of the sensibility with a factor to reduce the total range to a convenient number of units, 100 in this case. The scale obtained by Jones[10] by stepping off equal hue differences through the spectrum differs very imperceptibly from the scale obtained by integration. His data are given in the following table.

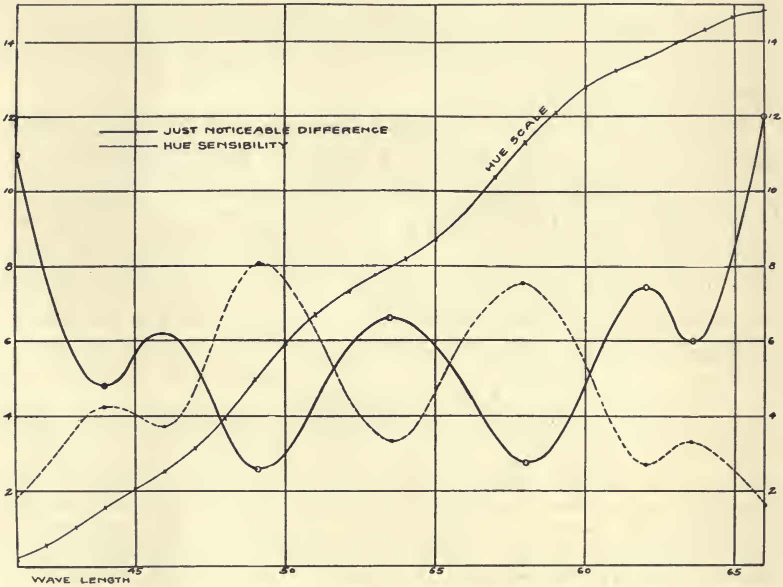

Figure 2. Hue Limen, Sensibility and Scale.

The amount of white that may be mixed with a pure hue before it becomes noticeable has been determined by the writer and L. A. Jones. Data are given in the following table.

Percent White	0,	10,	20,	30,	40,	50,	60,	70,	80,	90,	100
Percent Hue	100,	90,	80,	70,	60,	50,	40,	40,	20,	10,	0
Impurity Noticeable	4.7,	4.6,	4.5,	4.4,	4.2,	4.0,	3.7,	3.4,	3.0,	2.5,	2.1

Just Noticeable Hue Differences

No.	λ	δλ	No.	λ	δλ	No.	λ	δλ
1	700.0	....	44	576.5	1.4	87	490.4	1.1
2	678.0	22.0	45	75.2	1.3	88	89.4	1.0
3	65.0	13.0	45	73.7	1.5	89	88.2	1.2
4	59.0	6.0	47	71.7	2.0	90	87.0	1.2
5	54.0	5.0	48	70.1	1.8	91	85.8	1.2
6	649.5	4.5	49	568.4	1.7	92	484.5	1.3
7	46.0	3.5	50	66.6	1.8	93	83.2	1.3
8	42.8	3.2	51	64.8	1.8	94	81.7	1.5
9	40.2	2.6	52	63.0	1.8	95	80.0	1.7
10	37.8	2.4	53	61.1	1.9	96	78.2	1.8
11	635.5	2.3	54	558.6	2.5	97	476.5	1.7
12	33.1	2.4	55	57.0	2.6	98	75.0	1.5
13	30.0	3.1	56	54.4	2.6	99	72.9	2.1
14	26.5	3.5	57	51.8	1.6	100	70.5	2.4
15	23.0	3.5	58	49.1	2.7	101	68.2	2.3
16	620.0	3.0	59	546.1	3.0	102	465.8	2.4
17	17.3	2.7	60	43.0	3.1	103	63.6	2.2
18	14.9	2.4	61	39.8	3.2	104	61.2	2.4
19	12.5	2.4	62	36.5	3.4	105	58.7	2.5
20	10.2	2.3	63	33.2	3.3	106	56.5	2.2
21	608.0	2.2	64	530.1	3.1	107	454.4	2.3
22	06.0	2.0	65	27.1	3.0	108	52.1	2.3
23	04.1	1.9	66	24.2	2.9	109	50.0	2.1
24	02.3	1.8	67	21.4	2.8	110	48.0	2.0
25	600.6	1.6	68	19.1	2.3	111	46.0	2.0
26	599.0	1.6	69	516.8	2.3	112	444.2	1.8
27	97.4	1.6	70	14.6	2.2	113	42.5	1.7
28	95.9	1.5	71	12.6	2.0	114	40.8	1.7
29	94.5	1.4	72	10.6	2.0	115	39.0	1.8
30	93.1	1.4	73	08.0	1.6	116	37.2	1.8
31	591.8	1.3	74	507.0	1.0	117	435.3	1.9
32	90.5	1.3	75	05.4	1.6	118	33.3	2.0
33	89.5	1.0	76	04.0	1.4	119	31.3	2.0
34	88.5	1.0	77	02.6	1.4	120	29.3	2.1
35	87.5	1.0	78	01.3	1.3	121	27.0	2.2
36	586.4	1.1	79	500.0	1.3	122	424.8	3.2
37	85.3	1.1	80	498.7	1.3	123	22.3	2.3
38	84.0	1.3	81	97.4	1.3	124	19.7	2.8
39	82.7	1.3	82	96.1	1.3	125	16.7	3.0
40	81.5	1.2	83	94.8	1.3	126	13.8	2.9
41	580.3	1.2	84	493.7	1.1	127	401.4	3.4
42	79.1	1.2	85	92.6	1.1	128	405.8	4.6
43	77.9	1.2	86	91.5	1.1			

These data apply to red, green and blue; other hues have not been investigated. They apply to all moderate and high intensities (cone vision). Hue sensibility, previously discussed, is also independent of intensity over a wide range of moderate and high intensities.

Various color analyzers, properly called colorimeters, make analyses in terms of pure hue and saturation. The so-called monochromatic analyzers determine color in terms of wavelength of dominant hue and percent impurity. Trichromatic analyzers determine colors as ratios of three primary hues which when mixed will just match the known sample. On account of the difficulty of making absolute analyses, color comparators, sometimes improperly called colorimeters, are much used. These instruments merely serve to determine color matches between the unknown and some prepared standard of color. That standard may be a colored solution, a certain thickness of quartz between crossed nicols, or various mixtures of prepared pigments. One of the most extensive and most carefully prepared sets of comparison standards was prepared by Robert Ridgway of the Smithsonian Institution and gotten out by Hoen of Baltimore. Ridgway took 36 spectral hues and purples and diluted each with white in three steps and with black in three steps. Each primary hue is further diluted with gray and these in turn diluted with white and black. The whole set consists of 1113 colors differentiated from each other by about twice the least perceptible difference.

III. Sensibility to Intensity

The eye operates normally under intensities ranging from about 10 lamberts (the brightness of white paper in full sunlight) down to about one millionth of a millilambert. An average brightness out of doors on a clear day is about 1 lambert, in interiors during the day about 10 ml, in interiors at night 0.1 ml, out of doors at night, 0.001 ml. The adapted threshold of vision is about 0.0000007 ml. In operating over this enormous range of 20 billion to one, the eye far exceeds in range any other physical instrument. It is enabled to do this by automatically adjusting its sensibility to the brightness of the field viewed. The sensibility of the retina varies by a factor of about 10 million, while the brightness of the field viewed varies by a factor of approximately 10 billion. It is sometimes assumed that variation in size of pupil takes care of the widely varying range of intensity of field, but this is not the case, since the total range of pupillary diameters is but from about 2mm to 7.5 mm, or in area from 3 mm^2 up to 30 mm^2, a range of but 10:1.

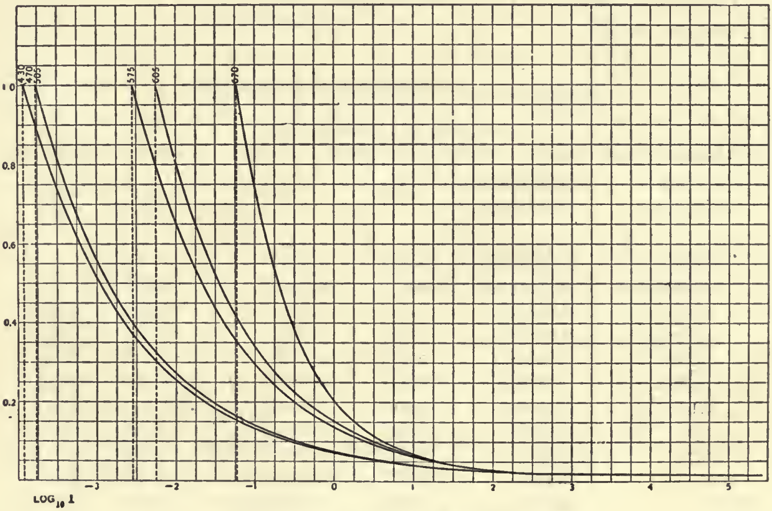

Figure 3. Contrast Sensibility.

It is of course impossible by direct measurement to determine the relation between brightness sensation and intensity of the stimulus producing that sensation. There are, however, various indirect means of determining that relation. With the retina adapted to any given field brightness, there is a corresponding (1) least perceptible brightness (threshold), (2) a least perceptible contrast in brightness either in juxtaposed fields or in alternating fields, and (3) an intensity just uncomfortably glaring. Determinations of each of these quantities have been made for normal vision throughout the whole range of operating brightnesses.

Threshold Sensibility is determined by means of the visual sensitometer[11]. A large cardboard illuminated to various known brightnesses is used to sensitize the eye. In the center of this field is a spot independently illuminated. After the eye is fully adapted, the light on the large sensitized field is suddenly switched off and the brightness of the spot adjusted so that it is barely visible at the first instant of switching off the light of the large field.

The data taken by means of this method are given in the following table.

Adaptation in Brightness Sensibility

(All values are in millilamberts.)

Field Brightness	Instantaneous Threshold	T/F	T_0/T	Log F	Log T
0.00000071	0.00000071	1.00	1.00	−6.15	−6.15
0.00000100	0.00000093	0.93	0.77	−6.00	−6.03
0.0000100	0.0000042	0.42	1.17	−5.00	−5.38
0.000100	0.000019	0.19	0.038	−4.00	−4.72
0.00100	0.000093	0.093	0.0077	−3.00	−4.06
0.0100	0.00039	0.39	0.0018	−2.00	−3.41
0.10	0.00175	0.017	0.00041	−1.00	−2.76
1.00	0.0082	0.0082	0.000087	0.00	−2.09
10.0	0.036	0.0036	0.000020	+1.00	−1.44
100.	0.191	0.0019	0.0000037	+2.00	−0.72
1,000.	2.140	0.0021	0.00000033	+3.00	+0.33
2,000.	3.980	0.0020	0.00000018	+3.30	+0.60

The data for white light is the mean of that taken by Blanchard, Reeves and myself; the three subjects agree with each other in absolute sensibility to within the uncertainty in a single set of readings. The curve is a straight line except at the ends and with a very slight dip in the region of ordinary brightnesses indicating that there the retina is a little more sensitive than normal. The bending off near the threshold is due to the test field being considerably smaller than the sensitizing field. The falling off from the linear relation at high intensities is due to failure of retinal adaptation at high intensities. If continued, the curve would cut the 45 deg. line at about 7.1 lamberts, indicating that the last named brightness is blinding. (See Fig. 4.)

Data of a similar nature have been obtained for the four colors blue, green, yellow and red by Blanchard[12]. His determinations, after correction for the Purkinje effect in the specification of intensities, coincides with the curve of threshold sensibility obtained for white light to within the error of determination.

Contrast Sensibility. If two fields of view side by side differ in brightness there exists a minimum difference in brightness which is just perceptible. The ratio of this brightness difference to the mean of the two fields is the well known Fechner fraction which is a constant over a wide range of intensities.

We are indebted to König and Brodhun[13] for the first investigation of contrast sensibility. Their data on white light and six pure hues are given in the following table. Their unit of intensity was roughly 0.0040 millilamberts. Intensities for the colored lights are given as fractions of high intensities all equal. If corrected for the Purkinje effect, the thresholds and all contrast ratios for all colors would be sensibly equal at each intensity.

Contrast Sensibility

Wave-Length	.670	.605	.575	.505	.470	.430	White
Field Br.	Least Perceptible Contrast						
1,000,000							0.0358
500,000							0.0273
200,000		0.0425					0.0267
100,000		0.0241	0.0325				0.0195
50,000	0.0210	0.0255	0.0260				0.0173
20,000	0.0160	0.0183	0.0205	0.0195			0.0175
10,000	0.0156	0.0163	0.0179	0.0181			0.0176
5,000	0.0176	0.0158	0.0166	0.0160			0.0179
2,000	0.0165	0.0180	0.0180	0.0175	0.0180		0.0181
1,000	0.0169	0.0198	0.0185	0.0184	0.0167	0.0178	0.0178
500	0.0202	0.0214	0.0180	0.0194	0.0184	0.0214	0.0192
200	0.0220	0.0225	0.0225	0.0220	0.0215	0.0245	0.0222
100	0.0292	0.0278	0.0269	0.0244	0.0225	0.0246	0.0298
50	0.0376	0.0378	0.0320	0.0252	0.0250	0.0272	0.0324
20	0.0445	0.0460	0.0383	0.0295	0.0320	0.0345	0.0396
10	0.0655	0.0610	0.0582	0.0362	0.0372	0.0396	0.0477
5	0.0918	0.103	0.0888	0.0488	0.0464	0.0494	0.0593
2	0.1710	0.167	0.136	0.0655	0.0715	0.0600	0.0939
1	0.258	0.212	0.170	0.0804	0.0881	0.0740	0.123
0.5	0.376	0.276	0.208	0.0910	0.096	0.0966	
0.2		0.332	0.268	0.110	0.127	0.116	
0.10			0.396	0.133	0.138	0.137	
0.05				0.183	0.185	0.154	
0.02				0.251	0.209	0.223	
0.01				0.271	0.289	0.249	
0.005				0.325	0.300	0.312	
0.002						0.369	
Threshold	0.060	0.0056	0.0029	0.00017	0.00012	0.00012	0.00072

These data may be fairly accurately represented by the function $P = P_m + (1 - P_m)\ (F/F_o)^{-n}$. The values of the exponent *n* in this equation are given in the following table for the six different wave-lengths.

	F_o	n	$P_m^{1/n}$	$P_m^{1/n}/F_o$
670	0.060	0.584	0.000832	0014
605	0.0056	0.388	0.0000234	0042
575	0.0029	0.364	0.0000116	0040
505	0.00017	0.335	0.00000434	0025
470	0.00012	0.323	0.00000276	0023
430	0.00012	0.323	0.00000276	0023

These values of course are only measures of the Purkinje effect. If the contrast sensibilities had been reduced to equal brightness sensations, the values for the different hues would have been sensibly equal and equal to the value for white.

Similar data have been obtained by Blanchard[12] and the writer using the visual sensitometer as devised by the writer. Contrast strips of varying densities were fastened across the test spot and adaptation curves run for contrasts of 0, .39, .67, .87 and .97. Our data check those of König and Brodhun, provided their unit of intensity was 0.0040 ml.

In the following table are summarized data on contrast sensibility over a wide range of field brightnesses. In the third column headed Discrimination Factor are plotted the reciprocals of the Fechner fraction, this being a measure of the relative ability of the eye to detect slight contrasts at the various intensities. The threshold limit is that previously given. In the fifth column are given data obtained by multiplying the difference fractions by the field brightnesses. This quantity is the difference in millilamberts between the two fields which will appear just perceptibly different in brightness at each intensity. It is to be noted that this difference over a wide range of moderate intensities is just twice the threshold limit to within the error in measurement. In other words, the difference in millilamberts between fields just noticeably different in contrast is twice the minimum perceptible brightness for an eye sensitized to the same mean field brightness. For example, with a mean field brightness of 0.1 ml, a rough average for interiors at night, the least perceptible difference is about 0.0037 ml, while the threshold limit is 0.00174 ml. The intensities indicated by initials in parenthesis are rough averages of those of most particular interest. The table on the following page gives data relative to field brightness, difference fraction, discrimination factor, threshold limit, difference and glare limit.

Field Brightness	Difference Fraction	Discrimination Factor	Threshold Limit	Difference	Glare Limit
0.000001 ml	(1.00)	1.0	0.00000093 ml	0.0000010	20.1 ml
0.00001	(0.66)	1.5	0.0000042	0.0000066	40.7
0.0001	0.395	2.5	0.000019	.0000395	89.
0.001 (E.N.)	0.204	4.5	0.000087	.000204	86.
0.01	0.078	12.8	0.00039	.00078	400.
0.1 (I.N.)	0.037	27.0	0.00174	.0037	810. ml
1.0	0.0208	48.2	0.0081	0.0208	1.66 l.
10. (I.D.)	0.0174	57.5	0.036	.174	3.47
100.	0.0172	58.1	0.28	1.72	7.25
1000. (E.D.)	0.0240	41.7	2.15	24.0	14.45
10000.	(0.048)	(20.9)	(232.)	480.	30.90

0.001 ml (E.N.) Exteriors at night, street lighting.
0.01 ml (I.N.) Interiors at night, interior artificial lighting.
1.0 ml (I.D.) Interior daylight lighting.
1.0 l. (E.D.) Exterior full daylight lighting.

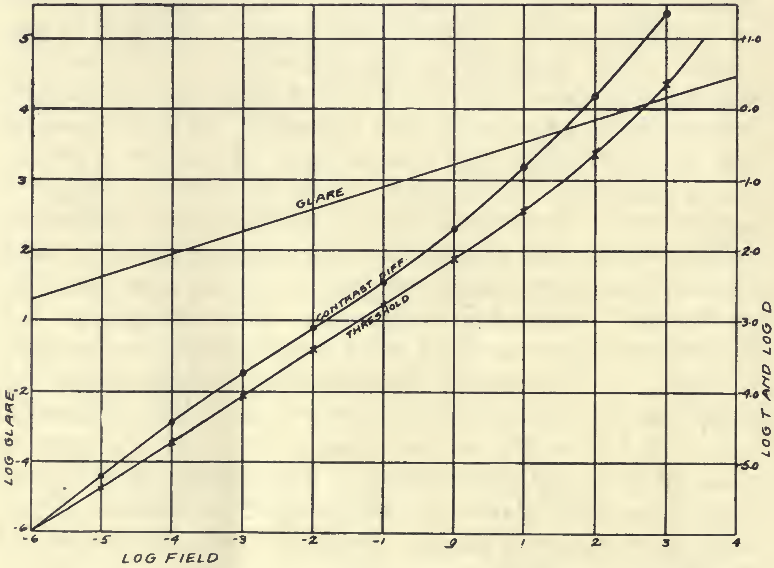

Figure 4. Threshold, Contrast Difference and Glare at Various Field Intensities.

In figure 4 are plotted the logarithms of the just perceptible thresholds and contrast differences each in millilamberts for various brightnesses of field viewed. Both are linear functions of the field brightness and they are sensibly parallel. The mean slope of each line is $2/3$ as closely as it can be read.

Taking sensibility as inversely proportional to these just perceptible intensities, we have therefore sensibility, $B :: F^{-2/3}$. The constant of proportionality is quite arbitrary. If it be taken such that sensibility is unity at the threshold, then we should have $B = (F/F_o)^{-2/3}$.

We are now in a position to determine the brightness sensation as a function of the stimulus by integrating the sensibility. This integral of $B \cdot dF$ gives for the sensation, $S = 1/3 F_o^{2/3}(F^{1/3} - F_o^{1/3})$. Hence we have it that the sensation is proportional to the cube root of the brightness of the field viewed except at the lowest intensities, the constant of integration being so chosen that the sensation becomes zero at the threshold. This cube root sensation law rests primarily upon the balance between the catabolic and metabolic processes in the visual purple. The energy flux per unit area at the retina is proportional to the brightness as defined and used in this paper.

Glare Sensibility. In response to the need of automobile headlight engineers for data on brightnesses just intense enough to appear uncomfortable, determinations were made by the author, Mr. Blanchard and Mr. Reeves.[12] The retina was sensitized to a definite field brightness, then a much brighter field suddenly flashed on. The three observers agreed surprisingly closely in their glare determinations, although these were made at different times and each observer formed his own criterion for judging glare. The mean results are given in the last column of the preceding table and plotted in figure 4. The logarithm of the glare is a linear function of the logarithm of the field brightness, the slope of the line being 0.32. From the slope and position of the glare line, brightness, $G = 1700F^{0.32}$. If the glare line be continued slightly, glare becomes equal to the field, or adaptation ceases at a field brightness of about 52 lamberts, five times as bright as white paper in direct sunlight. At night out of doors an average brightness is .001 ml and with the eye adapted to this average brightness, a field of 186 ml will just appear uncomfortably bright if suddenly flashed in the center of vision.

It is remarkable that both sensation and glare are proportional to the cube root of the brightness of the field viewed. This is less remarkable when we consider that the glare limit is a direct measure of the brightness sensation. From the last two equations it follows that if the unit of sensation is such that sensibility is unity and sensation zero at the threshold, then the glare limit is precisely 13 million times the sensation at each field of brightness.

IV. Rate of Adaptation

If the eye is adapted to one mean brightness of field of view,—that is to say a given flux density of energy into the retina—and the mean brightness of that field is then abruptly increased or diminished to another general level, the retina adapts itself to the new level of brightness at a given rate. The bulk of the adaptation takes place in the first few seconds but in extreme cases continues at a gradually decreasing rate for many hours.

The visual sensitometer previously mentioned was devised by the writer primarily to study the rate of adaptation from one level to another. With this instrument a wide variety of adaptations may be studied very readily, since intensities are varied by sliding along a black wedge whose density is quite accurately proportional to the distance from the thin end. Our observations thus far have been chiefly on rate of adaptation from light to darkness using various initial brightnesses, contrasts and colors, but the instrument is equally well adapted for determining adaptation from darkness to light. An earlier set of observations indicates quite clearly the general character and range of the phenomena involved. In this the eye was sensitized to a mean brightness of 25 ml, then this light suddenly switched off and the rate of increase in sensibility determined. Then the eye was fully adapted to darkness and suddenly exposed to a field brightness of 25 ml and the rate of sensibility decrease determined. These rough results are given in the following table.

Rates of Increase and Decrease of Sensibility

	$B_0=0$, $B=25$ ml.	$B_0=25$ ml., $B=0$
Time	Sensibility Decrease	Increase
1 second	2.1 times	1.6 times
2 seconds	4.2 "	2.6 "
5 "	16.2 "	7.6 "
10 "	58. "	14.4 "
10 minutes	120. "	20.9 "

For example, if an eye adapted to darkness be suddenly exposed to 25 ml its sensibility drops to 1/16 in 5 seconds and a subsequent rest of 10 seconds will by no means restore its sensibility. An alternation of equal exposures to a light field will therefore produce a decided depression in sensibility. The application of such data in practice is obviously of importance as for instance in passing along an ordinary lighted street at night.

The general phenomena of dark adaptation[12] are indicated in figures 5 and 6. The initial steady states from which adaptation proceeded were 0.1, 1.0, 10 and 100 ml. Curves are shown for each initial brightness, one set magnified in time to show the initial stages. These curves are not purely logarithmic as might have been anticipated. The sensibility taken as reciprocal of the just perceptible brightness of test spot is roughly proportional to the time of adaptation. This is shown in figure 6. When the pre-adaptation field brightness is small, the initial rise of sensibility is considerably greater than when the initial field is bright.

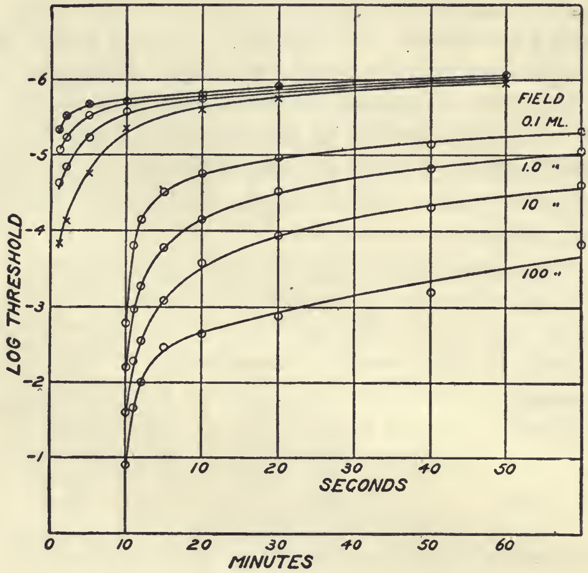

Figure 5. Dark Adaptation, White Light.

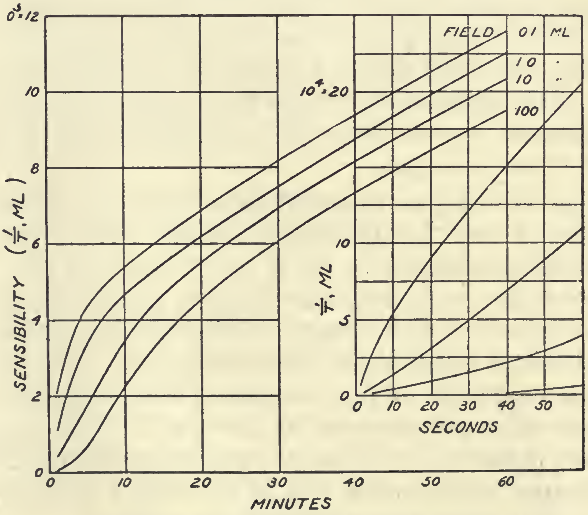

Figure 6. Dark Adaptation, White Light.

The rate of adaptation varies considerably with the color of the light used as shown in figure 7 for the colors red, yellow, green and blue. The adaptation to red light is more rapid but does not proceed as far as that for blue light. Green and yellow give intermediate rates of adaptation. The rate for white of the same initial intensity lies between those for yellow and for green.

Other determinations were made of the time necessary to just detect certain fixed contrasts; 0, .39, .67, .86 and .97. The results obtained are shown in figure 8. These data were obtained by fixing across the test spot strips of film whose transmission coefficients had the above values. Adaptation to slight (0.97 : 1) contrast is rapid but reaches nearly its final value in less than two seconds. Greater contrasts require longer and proceed farther in their adaptation. The same data plotted in a different way is shown in figure 9. These curves show the contrast just perceptible after a given time of adaptation. They are to be compared with the contrast sensibility curves of figure 3. From our data König and Brodhun in their determinations of contrast sensibility evidently waited for nearly complete adaptation before making their determination.

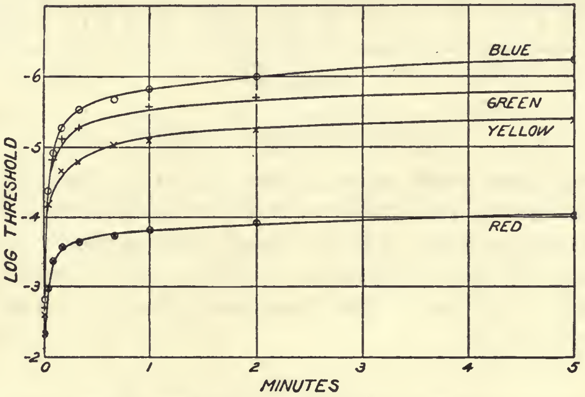

Figure 7. Dark Adaptation, Colored Light.

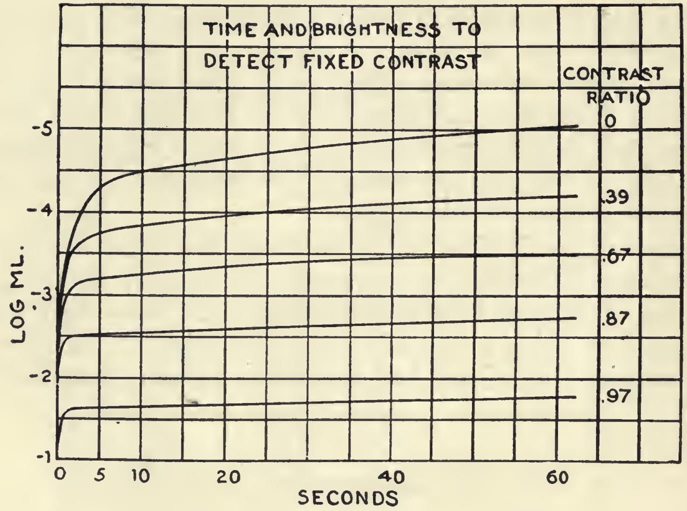

Figure 8. Adaptation to Contrast.

Reeves has made some interesting observations on the effect of size of test spot on contrast sensibility. The contrast used was 0.67. The test spots were squares of the size indicated in the table below. These were viewed from a distance of 25 cm. The data are given in logarithms of brightness in ml.

Effect of Size of Test Spot on Contrast Sensibility,
Contrast 0.67

Adaptation	3 cm sq.	2.5 cm sq.	1.5 cm sq.	0.7 cm sq.	0.3 cm sq.	0.2 cm sq.
0 second	−2.42	−2.10	−1.90	−1.69	−1.49	−1.31
2 seconds	−3.03	−2.64	−2.30	−1.91	−1.76	−1.46
10 "	−3.25	−2.93	−2.49	−2.11	−1.87	−1.58
60 "	−3.52	−3.25	−2.69	−2.27	−1.97	−1.69

It may be noted that the eye is nearly 100 times as sensitive for the 3 cm sq. test spot as for the 2 mm sq. test spot. This corresponds to the well known fact, namely that signboards which are to be read quickly at night must be printed in large letters with heavy contrasts to be easily legible.

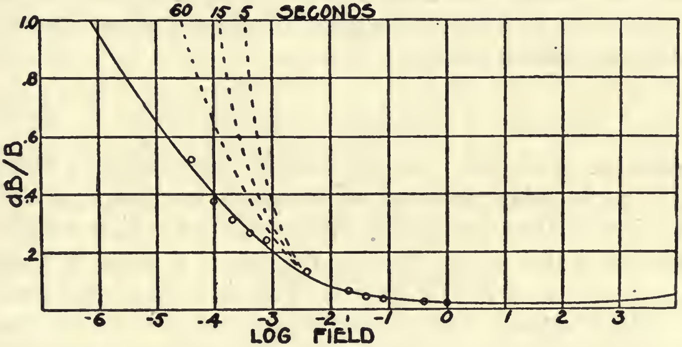

Figure 9. Contrast Sensibility, Contrast Adaptation.

Critical Frequency. The frequency at which flicker just disappears depends upon alternate light and dark adaptation of short period. Critical frequency is quite simply related to the brightness of the field viewed and has been used quite extensively as a method for research in visual sensitometry. Porter[14] found that for white light the critical frequency at moderate and high field brightnesses is a linear function of the logarithm of the field

$$N_1 = 12.4 \log F + 24.9$$
$$N_2 = 1.56 \log F = 19.6$$

The second relation holds at low intensities down to the threshold. The field brightnesses are here given in meter candles. The logarithms are common logarithms and the frequencies are alterations per second of equal light and dark exposures. As a means of measuring illumination, however, the critical frequency is rather insensitive.

Similar work has been done by Ives[15] for various monochromatic pure hues. The relation between critical frequency and field brightness is linear throughout for red light.

For blue light, critical frequency is independent of brightness for all intermediate and low brightnesses. For other colors the relations are intermediate between these two extremes. Allen[16] has used a critical frequency method with great success in the investigation of after images in relation to the color vision theory.

V. Absolute Sensibility

Diameter of Pupil. All the data in the preceding sections of this paper were obtained with the normal pupil, with the exception of that on critical frequency for which a light in lumens or watts per sq. mm at the retina is directly proportional to the area of the pupil as well as to the brightness of the object viewed. All visual sensitometry involves the relation between size of pupil and mean brightness and angular size of object viewed.

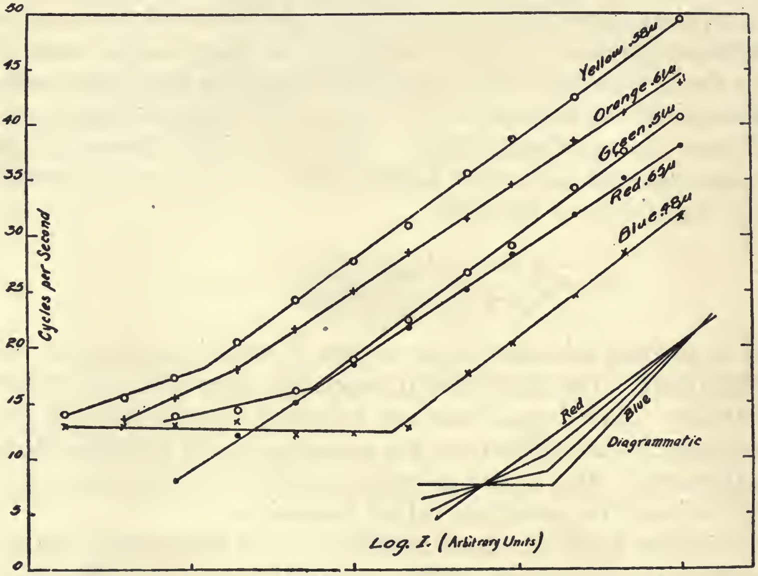

Figure 10. Critical Frequencies—Brightness and Color.

Various pupilometers have been suggested and used for determining the size of pupil, but it remained for Blanchard and Reeves[12] to actually make precise determinations. This was accomplished by flashlight photography. The results of their work are shown graphically in Fig. 11. Data were obtained for both eyes opened and for one eye closed during the sensitizing period. At a brightness of 1 ml, having the other eye closed makes a difference of fully 30% in the diameter of the pupil observed.

Other data are given in the following table.

Retinal Flux Densities

Field, Ml.	Observed Diameter of Pupil	Effective Diameter of Pupil	Area Effective	Lumens per mm²	Lumens per mm²/ml.
F	D		S	E	
0.00001	7.30	8.17	52.2	7.0×10^{-12}	7.0×10^{-7}
0.001	6.97	7.80	47.8	6.4×10^{-10}	6.4
0.01	6.65	7.44	43.4	5.8×10^{-9}	5.8
0.1	6.00	6.72	35.4	4.7×10^{-8}	4.7
1.0	5.06	5.66	25.1	3.3×10^{-7}	3.3
10.	3.86	4.32	14.6	1.9×10^{-6}	1.9
100.	2.72	3.04	7.25	9.7×10^{-5}	.97
1,000.	2.08	2.32	4.23	5.6×10^{-5}	.56
	2.00	2.24	3.94	1.1×10^{-4}	.11

In the final column of this table are given the lumens per sq. mm at the retina per ml of field brightness. The calculations in the 5th column are based on the equation $L = 1/\pi \times 10^{-5}\, FSn^2/v^2$, in which L is in lumens per sq. mm, F is field brightness in ml, S is the area of the effective pupil, n the mean refractive index of the eye media (taken as 1.34), and v is the equivalent back focal length of the eye (taken as 20.7 mm). The reduction factor of 1.14/1.02 was used to reduce from the observed apparent diameter of pupil to the actual entrance pupil of the system.

Minimum Perceptible Radiation. Reeves[17] has recently published some interesting data on the minimum energy necessary to excite the sensation of light. This is not a

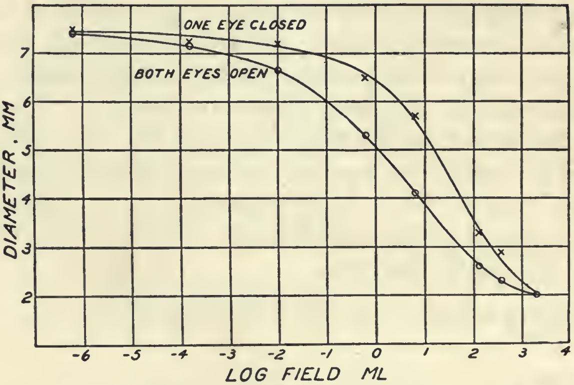

Figure 11. Diameter of Pupil for Different Field Brightnesses.

matter of light intensity alone but involves both angular area of object (area of retina exposed) and the time of exposure. His data on the relation between threshold and angular area are given in the following table:

Variation of Absolute Threshold of the Retina
with Size and Shape of Stimulus

Stimulus	Log. Threshold	Threshold (Ml)	Energy Entering Eye (Ergs per sec.)
1-mm star at 3 m	−2.14267	0.00720	17.1 x 10^{-10}
“ “ “ 1.5 m	−2.58503	.00260	24.8 x 10^{-10}
“ “ “ 35 cm	−3.61979	.00024	42.1 x 10^{-10}
2-mm square at 35 cm	−4.54837	0.000028	25.3 x 10^{-10}
5- “ “ “ “ “	−5.17881	66	37.
1-cm “ “ “ “	−5.61744	24	54.
2- “ “ “ “ “	−5.99012	102	91.
3- “ “ “ “ “	−6.34659	450	90.7
6- “ “ “ “ “	−6.58872	258	208.
12- “ “ “ “ “	−6.75647	175	564.

The energy entering the eye was calculated from the formula $SFMr^2/R^2$ ergs per second in which *S* is the area of the test spot in cm^2; *F*, its brightness in lamberts; *M*, the mechanical equivalent of light, here taken as 1.59 ergs per second per cm^2, r the radius of the pupil, R the distance of the eye from the stimulus in cm. As the mechanical equivalent of light has never been determined with any precision at these low intensities, the value used (1.59) may be subject to a very considerable correction factor.

Time is an essential factor in determining sensibility at these low intensities, as though the light were integrated in some way to produce the threshold effect, which is, of course, dependent upon the ultimate reactivity of the retina, just as the glare limit marks the minimum reactivity. The data in the table below were obtained by using a carefully calibrated focal plane shutter for determining the time of exposure necessary, the test spot being 3cm^2 at a 35 cm distance. The approach to constancy in the energy density of the retina given in the final column is very interesting indeed.

Variation of Absolute Threshold of the Retina
with Time of Exposure to Stimulus

Time (Sec.)	Log. Threshold	Threshold (Ml)	1/T	T x Time (Ml Sec.)
0.002	−3.44092	0.00036230	2.76	$.0_672$
.006	−4.01092	9752	10.3	58
.011	−4.35	4458	22.4	50
.020	−4.62	2394	41.7	48
.034	−4.91	1228	81.5	42
.160	−5.15	706	142.	$.0_511$
.250	−5.29	512	195.	13
.500	−5.45	345	282.	18
1.000	−5.58	00262	382.	26
2.000	−6.11	77	1300.	15
4.000	−6.20	63	1588.	25

If the time of exposure is very much decreased, similar effects have been noted even at moderate and high intensities. Blondel and Rey[18] found that the sensation was proportional to the energy entering the eye in the first fraction of a second of time of exposure. Much important work remains to be done in this entire field of research.

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Erythropsia

Charles Sheard, Ph.D.

ERYTHROPSIA, or red vision, is a condition, generally only temporary, in which the subject finds a more or less ruddy tinge on everything seen. Erythropsia is, therefore, the name of a phenomenon rather than that of a pathological condition. The tint of the coloration and the period of its observation are not definite: Fuchs in his monograph compares the color to a strong fuchsin solution with a trace of eosin solution. These cases may be clinically divided into three classes. First of all are the cases of erythropsia associated with neurosis such as those given by Charcot and others. There is no association in such cases with pathological conditions. There are, again, many recorded instances of red-vision due to traumatism and these are evidently due to infiltration of the eye media with blood. A considerable number of cases, as a third division—and this class constitutes the majority—, are associated with over-exposure to light. Several writers, including Widmark and Fuchs, have attributed the average condition of erythropsia to the effects of ultra-violet radiations. Furthermore, Fuchs advanced the theory that the regenerating visual purple accounted for the red-vision as an entoptic phenomenon. Schulek produced erythropsia by observing spectral ultra-violet as also did Birch-Hirschfeld some time later. The experiments of Vogt in 1912, however, indicated that erythropsia had no connection with specific radiation but that it was a general phenomenon of color vision. Quite recently Weydler has investigated the subject thoroughly and has concluded that erythropsia is due to the red phase of the negative after-image following over-exposure to light, this light ordinarily being of a brilliant white in color although green and blue-green illumination is even more effective. That the ultra-violet *per se* has nothing to do with the production of these conditions was demonstrated by Vogt. For he found that erythropsia could not be produced experimentally by the ultra-violet rays alone but could be very easily produced by light rays having no ultra-violet constituent. It has been found possible to produce marked erythropsia through Euphos glass (which transmits little if any ultra-violet), through B-naphthol-disulphonic acid (which cuts off the ultra-violet) and through dense flint glass of such a character as to eliminate all of the shorter wave-lengths classed as ultra-violet which could get through and impinge upon the retina. Furthermore, it is easily produced by radiation through green and blue-green screens and media which completely absorb the ultra-violet and practically eliminate the extreme violet but which allow the entrance of light of a color such as will produce a strong red phase in the after-image. The upshot of the whole matter, therefore, appears to be that the so-called photo-erythropsia is a consequence of such an unequal fatiguing of the primary color sensations as to leave for a greater or lesser period of time thereafter a strong red phase of the after-image or a color sensation predominantly red. Experiments made by Birch in 1899 throw considerable light upon this matter. If any of the primary color sensations are fatigued that of the remaining color or colors becomes the predominant tint seen. Birch found that of the three primary colors—red, green and blue—the red first regained its sensibility after a period of about ten minutes ordinarily, followed by the green and last of all by the blue. Red vision is, therefore, normally to be expected after fatigue of all three sensations since the red recovers first, and in the condition that the green and blue are more fatigued than the red the latter will be the more notably predominant.

Following out the logic of the conclusions of the foregoing experiments it would appear that the red-vision commonly occurring when eyes are exposed to the radiations from snow on a bright day is due to fatigue of all color sensations under the stimulus of the excessive quantity of radiant energy reaching the retina, with the result that the red regains its sensibility first. The cause cannot be attributed, if we accept the results of Vogt's experiments, to ultra-violet radiation which we know to be reflected in large percentage from a surface of snow. Furthermore, so far as the solar spectrum is concerned the heat energy is chiefly within and very close to the visible region. No distinction, therefore, should be drawn between the visible and the infra-red spectrum on the ground of heat radiation. Hence the effect of energy in excessive amounts from surfaces of snow appears to be the sole effect of this and other physiological reactions in the eye.

A form of erythropsia due to the probable effect of the coloration of the crystalline lens previous to removal in cataractous conditions has been noted by Weydler. Since the lenses often assume with age a yellow color and since the eyes are generally shielded against any excess of the blue and violet, it is often found that, following cataract extraction, an eye exposed to daylight will experience a red-vision condition after fatigue.

Abstracts and Reviews

Relative Sensibility of the Average Eye to Light of Different Colors and Some Practical Applications to Radiation Problems

W. W. Coblentz and W. B. Emerson

THIS long and important investigation by Coblentz and Emerson occupies about seventy-five pages of Bulletin No. 2, Volume 14, of the publications of the Bureau of Standards.

The difficulties encountered in determining the relation between luminous sensation, "light" and radiant energy—*i.e.* the relative visibility of radiation in different parts of the spectrum—are due to the fact that the relative brightness varies not only for different colors but also for changes in size and brightness of the illuminated field. The various methods adapted to determining the visibility of radiation include (1) threshold of vision, (2) visual acuity, (3) critical frequency, (4) equality of brightness and (5) the flicker photometer.

In their investigational work Coblentz and Emerson used a high grade spectrometer giving no diffuse light, a cylindrical acetylene lamp the intensity of whose light is quite constant, and other necessary accessory apparatus. The distribution of energy in the spectrum of the acetylene lamp was determined by exploring the complete visible spectrum with a thermopile. Nicol prisms were used to vary the intensity of the light falling upon the slit and hence to vary the intensity in any portion of the spectrum. The photometric measurements were made with the flicker photometer; this instrument could also be adjusted to make the equality-of-brightness measurements.

One of the most interesting parts of this paper has to do with the effects of total and partial color-blindness on the relative visibility of radiation. In the case of total color-blindness the maximum intensity is in the region of 5200 t.m., while for the normal eye (average) it is at about 5600 t. m. From this it would appear that the color perception in the case of so called total color-blindness is similar to that of the normal foveal color vision under very low illumination and to that of rod vision (*i.e.* peripheral vision) under high illumination.

Jeffries, Ferry, Allen, Tufts and others have investigated the points of maximum visibility for partially color-blind persons. The results of Coblentz and Emerson show, for example, that in a case of red-blindness the visibility curve is unusually low in the red and high in the blue.The results of their investigations are in agreement with those of Ferry and Tufts and others, showing that the effect of light upon the color sense is quite independent of its effect upon the brightness sense. An abnormal color sense is associated with an abnormal (brightness sensibility) visibility curve; but the converse is not true, as is shown by the examples of abnormal visibility curves of persons having normal judgments in sorting and matching colors. Red sensitiveness and blue sensitiveness cause small shifts of the visibility curves bodily toward the red or the blue, respectively. In the case of green-sensitive subjects the response of the red and blue is not up to the average eye. Correspondingly a class of persons, few in number, possessing red-blue sensitiveness, have sensibility curves very wide as compared with the normal curve. In the case of subnormal blue or red sensitive persons, the visibility curves coincide with the average visibility curves throughout the spectrum except in the blue-violet and the orange-red, respectively.

All tests made indicate that fatigue and the condition of adaptation of the eye when examined as to its visibility in various portions of the spectrum have very small if any effects.

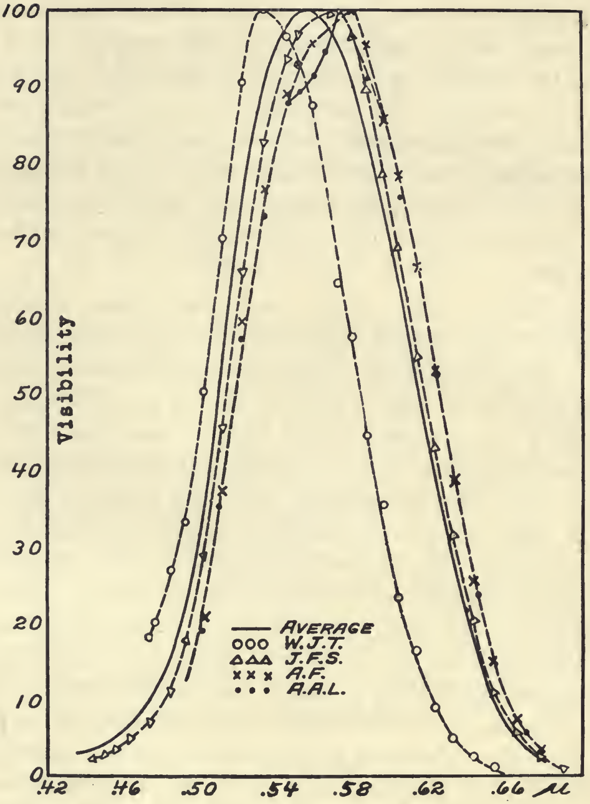

Fig. 1. Spectral Sensibility Curves of Eyes affected by Partial Color-blindness.

From the data obtained on fourteen observers above forty years of age it appears that age has a perceptible effect upon the spectral-visibility curve. The average curve for those over forty coincides with the average eye curves of persons between twenty-two and thirty-two years of age in the region lying between 7200 t. m. (red) to 5200 t. m. (blue) and falls inside of the average curve in the blue-violet region. (The effect is doubtless due to the fact that the absorption of the

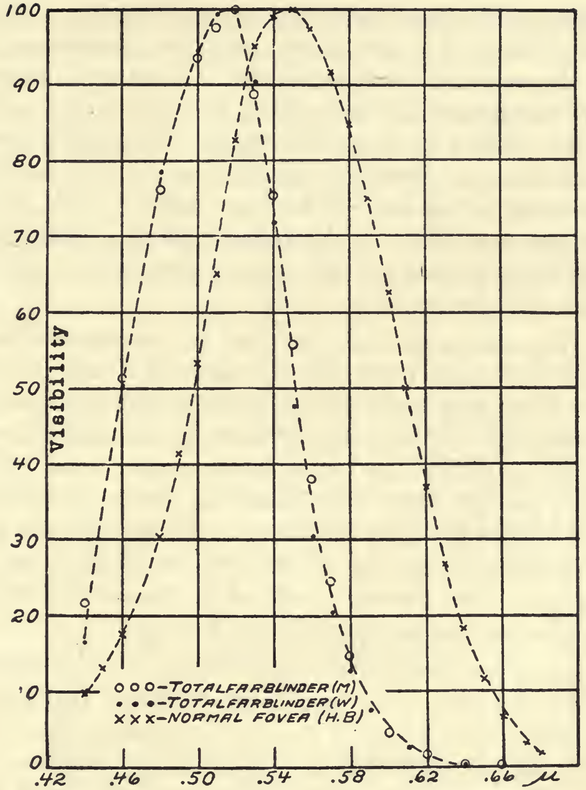

Fig. 2. Relative Sensibility of the Eye to Different Wave-lengths in the Case of Total Color-blindness.

crystalline lens in the blue-violet region increases with age. C. S.)

In closing their paper Coblentz and Emerson say: The spectral-visibility curves of no two persons appear to be exactly alike, although there are some which are closely alike. When a spectral-visibility curve does not coincide with the average, there is usually a marked departure from the average visibility in a given spectral region. This gives rise to (1) wide visibility curves with the maximum shifted toward the red, *i.e.* "red sensitive," (2) narrow curves with a sharp maximum in the green, and (3) curves with the maximum shifted toward the violet. A fourth group of observers has the average visibility in the red and yellow, but has a low sensibility in the blue, while a fifth group has the average sensibility in the blue but has a low sensibility in either the yellow or the red or throughout this entire region of the spectrum.

The data available indicate that 60 percent of the cases examined fall into three quite evenly divided groups (*i.e.* 20 per cent roughly estimated in each group) which are either (1) red sensitive, (2) blue sensitive or (3) average. Similarly, 30 per cent of the cases examined are quite evenly divided into three groups which fall below the average sensibility in either (1) the red, (2) in the blue, or (3) in both the red and the blue, thus giving rise to an apparently high sensibility in the green. One person in about 20 has a very wide visibility curve as compared with the average.

The point of maximum visibility is very different for different observers. The maximum visibility of the average of 125 subjects is at 5576 t. m. Correcting the visibility curve of the average eye for selective transmission of the ocular media including the yellow spot, produces a quite symmetrical curve with a maximum at 5560 t. m.

(Abstracted from *The Bulletin of the Bureau of Standards*, Vol. 14, page 228.)

The Frame Power of a Lens

(Being one of a series of articles on The Best Form of Lenses.)

A. Whitwell, M. A.

THIS paper by Whitwell was written in response to a request for the calculation of the changes necessary in the strength of lenses (1) when changing from bi-convex to

+6 D. base toric or meniscus, (2) when changing from bi-convex to −6 D. base toric or meniscus and (3) when changing from bi-concave to +6 D. toric or meniscus.

It is necessary that, in the interchange of these forms of lenses, the focus be in exactly the same spot with respect to the eye when the lenses are worn in the same position.

For the sake of convenience Whitwell calls the reciprocal of the distance from the median plane of the spectacle frame to the focus the *Frame Power.* Hence two lenses will have the same frame powers when put in the same frame and worn in front of the eye.

In *A* of Fig. 1 is shown a double convex lens which is assumedly exactly sufficient to correct the errors of the eye and to focus a distant object on the fovea. Part *B* shows a meniscus of the same power which will not properly correct the same eye when placed in the same frame, while *C* shows a meniscus of slightly less power than the lens in *A* or in *B* which is equivalent to the double convex lens when placed in the same frame.

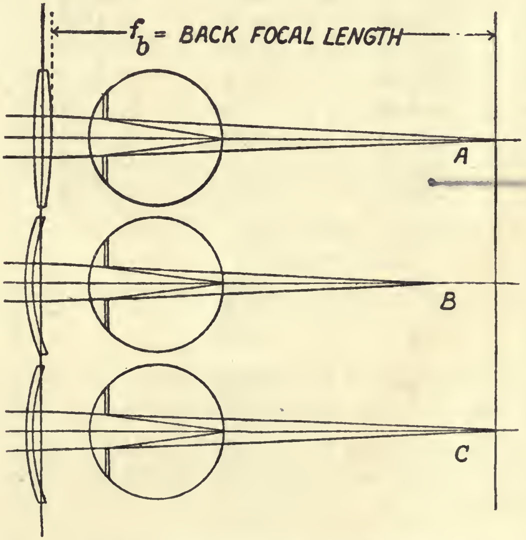

Fig. 1. Back Focal Lengths of Various Forms of Lenses.

The mathematical formulæ and calculations given by Whitwell are omitted in this review. Suffice to say that he takes the diameters of his lenses as 36 mms., the index as 1.52 and the rim thickness as 1.5 mm. and calculates in each case the thin lens power. The axial thicknesses of negative lenses are taken as negligible.

Instead of using the term *frame power* we could use the term *frame focal length* as meaning the distance of the focus from the medium plane of the frame; this term would be analogous to back focal length which is measured from the vertex of the last surface.

TABLE I

Frame Powers of Lenses of Various Forms

k_1+k_2	Dbl. Convex or Dbl. Concave	Base +6D	Meniscus Base −6D	Whitwell
+ 1D	+1D	+1.04	+ 1.07	+ 1.10
+ 2D	+2D	+2.05	+ 2.10	+ 2.15
+ 3D	+2.99	+3.06	+ 3.14	+ 3.21
+ 4D	+3.98	+4.06	+ 4.20	+ 4.28
+ 5D	+4.98	+5.06	+ 5.28	+ 5.40
+ 6D	+5.96	+6.05	+ 6.37	+ 6.55
+ 7D	+6.94	+7.04	+ 7.48	+ 7.79
+ 8D	+7.91	+8.07	+ 8.62	+ 9.05
+ 9D	+8.89	+8.97	+ 9.77	+10.21
+10D	+9.85	+9.92	+10.94	+11.36
− 1D	−1	−1		− 1
− 2D	−2	−1.99		− 1.99
− 3D	−3	−2.98		− 2.98
− 4D	−4	−3.96		− 3.96
− 5D	−5	−4.94		− 4.94
− 6D	−6	−5.90		− 5.92
− 7D	−7	−6.84		− 6.89
− 8D	−8	−7.81		− 7.86
− 9D	−9	−8.74		− 8.82
−10D	−10	−9.67		− 9.78

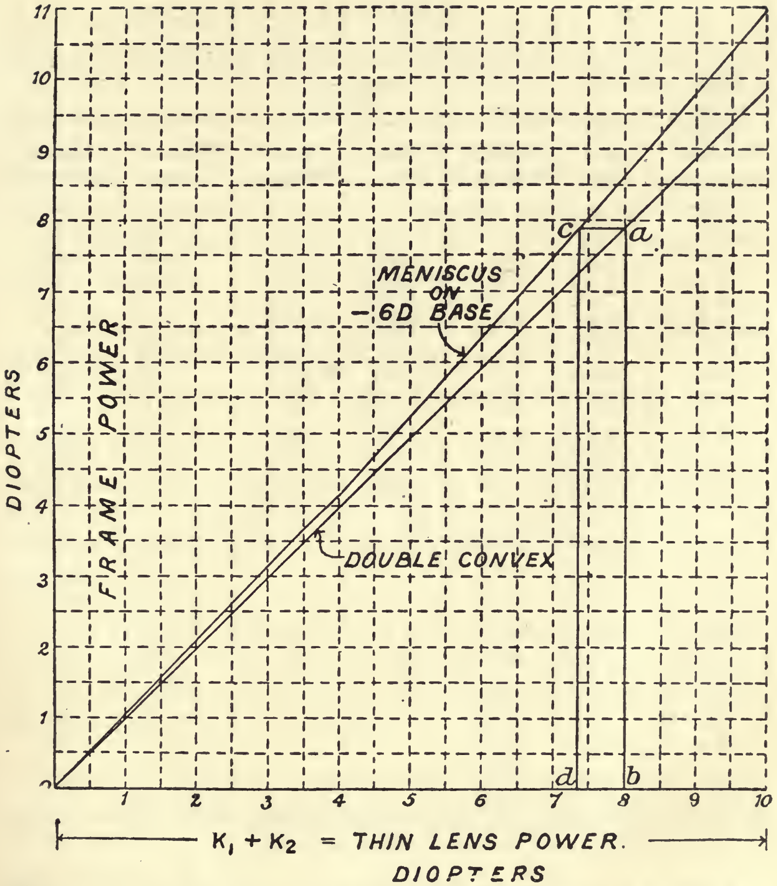

Fig. 2. Plot Showing the Relation between the Frame Power and the Thin Lens Power.

Table I gives the frame powers of lenses of various forms. In this table k_1+k_2 represents the sum of the refractive powers of the two lens surfaces. For example, if each surface measures on a lens gauge 1 D, then the sum of the two surfaces represents 2 D and physically is to be handled as the thin lens equivalent.

TABLE II

Equi-Convex or Equi-Concave Diopters k_1+k_2	Meniscus					
	Base 6D+	Approx. Difference	Base 6D−	Aprox. Difference	Whitwell Lenses	Approx. Difference
1+	1.00	0.0	0.94	0.0	0.92	0.00
2+	1.95	0.0	1.90	0.0	1.88	0.00
3+	2.94	0.0	2.88	0.25	2.83	.25
4+	3.91	0.0	3.80	0.25	3.73	.25
5+	4.93	0.0	4.71	0.25	4.63	.25
6+	5.90	0.0	5.60	0.50	5.48	.50
7+	6.88	0.0	6.50	0.50	6.30	.75
8+	7.88	0.0	7.38	0.50	7.10	1.00
9+	8.90	0.0	8.23	0.75	7.88	1.00
10+	9.93	0.0	9.08	1.00	8.58	1.50
1−	−1.00	0.0			−1.00	0.0
2−	−2.03	0.0			−2.03	0.0
3−	−3.05	0.0			−3.05	0.0
4−	−4.05	0.0			−4.05	0.0
5−	−5.08	0.0			−5.08	0.0
6−	−6.11	0.0			−6.08	0.0
7−	−7.18	0.25			−7.13	0.0
8−	−8.20	0.25			−8.15	0.0
9−	−9.29	0.25			−9.2	.25
10−	−10.35	0.25			−10.25	.25

Table I furnishes us the different frame powers of lenses of different forms having the same value of k_1+k_2. What are desired are the different values of k_1+k_2 for lenses of different forms having the same frame power. The different values of k_1+k_2 can be found by plotting the frame power against the thin lens power as shown in Fig. 2. In this figure the thin lens power is measured horizontally along the axis of x and the frame power, obtained from Table I, is measured vertically along the axis of y. The two curves correspond to an equi-convex lens and to a menicus on a $-$D base. To find the lens power of say a meniscus on a -6 D base which will have the same frame power as an equi-convex lens of which $k_1+k_2=8$ D+, we draw a vertical line, *a b*, through the division 8 on the horizontal scale and where this line cuts the equi-convex curve at *a* we draw a horizontal line, *c a*, to meet the meniscus curve in *c* and then another vertical line, *c d*, meeting the horizontal scale at *d*. The thin lens power of the meniscus is thus found to be 7.38 D.

Table II contains the answers to the three questions stated in the first paragraph of this article.

The conclusions in the form of worded statements are:

Case I. In changing from an equi-convex lens to a meniscus on a 6D+ base it is not necessary to make any corrections as the difference of the thin lens powers of the two different forms of lens is always less than a quarter of a diopter.

Case II. In changing from an equi-convex to a meniscus on a 6D$-$ base the correction is shown in column 5 being the difference between the figures in columns 1 and 4 to the nearest quarter diopter.

Case III. In changing from an equi-concave to a meniscus on a 6D+ base no corrections need be made below 6D but from -7D to -10D the power must be increased by a quarter of a diopter.

(Abstracted from the *Optician and Scientific Instrument Maker*, London, Vol. LVIII, No. 1492, 1919.)

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The American Journal *of* Physiological Optics

The Extent and Shape of the Zones of Color Sensitivity in Relation to the Intensity of the Stimulus Light

C. E. Ferree, Ph.D. and G. Rand, Ph.D.

Introduction

THE investigation of the limits of sensitivity may be considered from three points of view. (1) It may be made a part of the investigation of the comparative sensitivities of the peripheral retina to the different colors. (2) It may be considered more specifically in relation to points of theory. (3) It may be considered in relation to the diagnosis, more particularly the early diagnosis of various ocular diseases which cause abnormalities in the relative distribution of sensitivity to the different colors. In the first of these cases the limits should be obtained with stimuli equalized in energy. The results will then represent positions on the retina at which stimuli for one of the intensities which it is possible to employ have the same or nearly the same threshold value.* In the second case the problem considered in relation to its historical development divides into two parts: (a) determination of the relative or apparent limits and (b) a determination of the absolute limits. In a former paper[1] it was shown that the determination of the apparent limits was given an undue importance in relation to theory by Hess and his followers because of their failure to realize that great irregularity and not uniformity characterizes the decrease of sensitivity from the center to the periphery of the retina. The details of that demonstration need not be repeated here. The determination of the absolute limits of sensitivity, however, does sustain an important relation to theory, especially to theories of the paired process type; for if it be found that sensation can be aroused farther out from the center of the retina for one of the paired colors than for the other, that fact must tell against the theory unless some supplementary concept is provided to explain the discrepancy. For one thing we have undertaken, therefore, to determine the limits of sensitivity with stimuli any further increase of the intensity of which tends to decrease rather than to increase the chromatic response. For another, we have determined the effect of a given range of variation of intensities on the apparent limits. This latter point is important primarily because of its bearing on the needed control of test conditions in the laboratory and clinic and because of the light it throws on the results obtained in the laboratory and the clinic with stimuli not equably related and regulated as to intensity. In short, it is no small part of the purpose of the paper to show that the actual distribution of sensitivities is only one of the factors determining the apparent limits of sensitivity. With a suitable regulation or grading of the relative intensities of the stimuli, for example, the limits of sensitivity may be made to interlace or criss-cross, to reverse their places in the order of rating from widest to narrowest and to have, roughly speaking, almost any other rating that may be desired.

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*Strictly speaking the threshold value may be considerably less at this point than the intensity of the stimulus employed, because the stimulus may be increased much above the threshold value in the far periphery of the retina without changing the limits by a detectable amount. That is, the stimulus value of the just noticeable difference in limits is much greater than the stimulus value of the difference limen of intensity. In other words, a given point in the peripheral retina may be considered the limit for a range of stimulus intensities, varying in magnitude with its degree of excentricity.

The difficulty of getting reproducible results in determinations of the color sensitivity of the peripheral retina is a common complaint among laboratory and clinic workers. This is due to an inadequate standardization of the conditions under which the work is done. With a proper control of the factors which influence the chromatic response, the results of a perimetric or campimetric determination of sensitivity can be reproduced within a very remarkably small limit of error. These factors are, so far as we have been able to discover, the wave-length and purity of the stimulus, intensity of stimulus and the visual angle, length of exposure of the eye, accuracy and steadiness of fixation, the general illumination and state of adaptation of the retina, breadth of pupil, and the brightness of the pre-exposure and of the background, or surrounding field. The most important of these is the intensity of the stimulus light. By varying the intensity of the stimulus the zones of color sensitivity may, as already indicated, be made to have almost any extent within the limits of white light vision and to vary radically in shape.

The Problem

The investigation was given the following form. (1) An attempt was made to find out whether by means of a spectroscopic apparatus[2], which was designed especially to give high intensities of light, stimuli could be obtained which would be sensed as color to the limits of white light vision. (2) The effect on the extension of the limits and on the shape of the zones of sensitivity of varying the stimuli through quite a wide range of intensities was investigated. And (3) the determination of the limits was made in sixteen meridians with all of the lights made equal in energy to the blue of the prismatic spectrum employed and with 1/32 of this energy.

Conditions Under Which The Work Was Done

The conditions under which the work was done fall under five headings: (1) the wave-lengths of light employed and the means used of getting greater purity of light than is found in the prismatic spectrum; (2) the energy content of the stimuli used and the method of measurement; (3) the control of the brightness of pre-exposure and surrounding field; (4) the control of the general illumination of the optics room, and (5) the method of rendering the amount of light entering the eye independent of variations in the size of the pupil without the use of an artificial pupil.

(1) The stimuli employed were taken from the prismatic spectrum of a Nernst filament. They were a narrow band of red in the region of 670 $\mu\mu$, of yellow in the region of 581 $\mu\mu$, of green in the region of 522 $\mu\mu$, and of blue in the region of 468 $\mu\mu$. The spectrum was obtained and the peripheral retina exposed to stimulation by means of the apparatus described in the *Journal of Experimental Psychology*, 1916, I, pp. 247–284: A Spectroscopic Apparatus, etc. The light was examined in every case at the analyzing slit for impurities by means of a small Hilger direct-vision spectroscope provided with an illuminated scale. When found, impurities were absorbed out by thin gelatine filters, selected so as to cut out as little of the useful light as possible. These gelatines were placed over the analyzing slit and were held in position by short clips fastened to the front surface of the jaws, the edges of which formed the slit. (2) The specification of the light intensities was made in energy values. Measurements were made at two places: namely, the analyzing slit and the pupil of the eye. They were made for the higher intensities only. The lower intensities were obtained by means of sectored discs and their energy computed from the simple law of the disc. The apparatus and method used for making the energy measurements have been described in previous papers.[3]

(2). The stimulus used was the circular aperture of the campimeter, 15 mm. in diameter, filled with light by the focussing lens. At a distance of 25 cm. from the pupil of the eye, on which the light from the objective slit of the spectroscope was focussed, this aperture subtended a visual angle of 3 degrees and 26 minutes. The time of exposure was 1 second and the interval between exposures varied between 3 to 5 minutes, depending on circumstances and the need for precautionary measures. If the stimulus was sensed in the proper color at any time during the 1 second interval of exposure, the retina was called color sensitive at that point. The field in the 16 meridians was always mapped for one color before the work for another color was begun.

Systematic results were obtained for all of the points of the work for only one observer. For data with regard to the various ways in which the normality of both the chromatic and achromatic sensitivity of this observer, central retina, and chromatic sensitivity, peripheral retina, have been confirmed, the reader is referred to pp. 26–32 of "Chromatic Thresholds of Sensation from Center to Periphery of the Retina and their Bearing on Color Theory—Part I (*Psychological Review*, 1919, XXVI, pp. 26–32). Data on additional points important in a general specification of the ocular condition of the observer have also been published in various places: *e.g.*, on the dioptric or refraction condition and power to sustain acuity in *Transactions Illuminating Engineering Society*, 1915, X, p. 1128, and in other papers by us in lighting in relation to the eye; on muscle strength, muscle balance, muscle lag, photopic acuity, near point, range of accommodation, and refractive condition (more recent), *Transactions American Ophthalmological Society*, 1918, LXVI, pp. 142–163; and on scotopic acuity and amount and rapidity of scotopic adaptation, *Transactions American Ophthalmological Society*, 1919, LXVII.

The more important points, such as the coincidence of the limits of red, yellow and blue with the limits of white light vision, the narrow limits for green, the interlacing of limits for stimuli of medium intensity of equal energy or of the same general order of intensity, and the large differences in the amount of light required to change the limits of sensitivity by a detectable amount in the mid and far peripheral portions of the retina have been confirmed in a less detailed and systematic way by one or more check observers.

(3) Whenever possible, the surrounding field and pre-exposure were made equal in brightness to the stimulus as seen at the point at which the investigation was being made. For the stimuli at the highest intensities used, however, the white screen (coefficient of reflection about 75 per cent) illuminated by the light of the room was darker than the color used. For these intensities, therefore, a surrounding field and pre-exposure somewhat darker than the color had to be employed. The equalization was made in each case by the equality of brightness judgment for the point at which the investigation was being made. For want of better pigment materials, the surrounding field and pre-exposure were chosen from the Hering series of standard papers. In order to make the brightness specification of the surrounding field and pre-exposure independent of the illumination of the room and of the variability of the reflection coefficients of different issues of the Hering papers, the brightness was in each case specified in candle power per square inch. The determination of brightness was made by means of a Sharp-Millar portable photometer with the test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candle power per square inch by the following formula: Brightness = foot candles $/\pi \times 144$. For the sake of reproducibility of conditions from time to time in a given laboratory or in different laboratories, it is obvious that a photometric specification should be given in all cases, not only of the general illumination of the room but of the brightness of all surfaces for which precision of control is of importance to the results of the work.

(4) The illumination of the room was kept at a constant value. Two features are necessary for this control. (1) A means must be had of detecting small changes of illumination. This may be accomplished by the use of a portable photometer of the Sharp-Millar or Macbeth type, for example, furnished with a daylight screen, or of the simpler type described by the writers in a previous article. (A Simple Daylight Photometer, *American Journal of Psychology*, 1916, XXVII, pp. 335–340.) And (2) a means must be had also of producing small variations in the illumination of the room, else the changes due to fluctuations in the external light cannot be compensated for with the precision and minuteness of control that is needed. This is accomplished in our optics room by two systems of white curtains running on spring rollers beneath the skylight. One of the systems of white curtains and the light proof curtain run lengthwise of the room; the other system of white curtains runs across the room. By means of the white curtains either small local or small general changes can be produced in the illumination of the room; and by means of the light proof curtain larger changes may be produced ranging from full illumination to the darkness of a moderately good dark room. The light proof curtain is of a breadth equal to that of the room and runs in a deep light-tight boxing. The white curtains are narrower and are made to overlap at the edges. These curtains run on wire guides so distributed as to prevent any trace of sagging or wrinkling. Above these curtains are pivoted two large diffusion sashes of glass ground on one side, completely filling the skylight opening. These sashes diffuse the light in the room giving an even distribution of illumination and rendering, because of that fact, an even and precise control easier to accomplish. In a careful specification of the conditions under which the work is done a very important item is to give a photometric specification of the illumination of the room. This may be done in foot or meter candles as desired. If the illumination is

uneven it should be done systematically throughout the room. If, on the other hand, it is pretty uniform, it is usually sufficient to give its value in three or more directions at the point of work.

(5) The amount of light entering the eye was made independent of variations in the size of the pupil. Independence of change in size of pupil was especially needed in this work, because of the large variations in the intensity of light used. Such control is very easy to accomplish with the means of presenting the light to the eye that is used in our apparatus. All that is needed is to keep the image that falls on the pupil of a constant size and smaller than the pupil throughout its entire range of variations in the given series of experiments. Not only can this variation be determined in preliminary experiments as a guide to the size of the image that is needed, but the image itself can be compared with the pupil at each observation. For details of the method of exercising this control see "A Substitute for an Artificial Pupil," *Psychological Review*, 1916, XXIII, pp. 380–383.

Results

(1) It was quite easy to obtain an intensity of light for the red, yellow and blue wave-lengths that could be sensed to the limits of white light vision. In fact these wave-lengths in the spectrum employed were considerably above the threshold at the limits of white light vision in the sixteen meridians investigated. The limits of the green of this spectrum, however, fell far short of the limits for white light; nor could the zone of sensitivity be widened as much as 1 degree by increasing the current in the Nernst filament from 0.6 to 0.8 ampere. The energy entering the eye from the spectrum of the Nernst filament operated at 0.6 ampere of current with the width of collimator slit employed was for the red 9096.639×10^{-10} watt; for the yellow 4065.624×10^{-10} watt; for the green 1562.388×10^{-10} watt; and for the blue 882.025×10^{-10} watt. The energy value of the threshold at the

limits of white light vision in the nasal meridian, for example, was for the red 277.836×10^{-10} watt, for the yellow 268.95×10^{-10} watt; and for the blue 264.368×10^{-10} watt. The intensity of light for these colors in the 0.6 ampere spectrum was, therefore, strongly supra-liminal at the limits of white light vision as is stated above. In the 0.6 ampere spectrum, the energy of the green light, it will be noted, was greater than the energy of the blue but less than the energy of the red and yellow. It was, however, nearly six times as great as the threshold value of these colors at the limits of white light vision. Moreover, when the current was raised to 0.8 ampere, this value was considerably increased but there was still no detectable extension of the limits. Since then the sensitivity to green at the center of the retina and for several degrees towards the periphery is approximately the same as to blue and considerably greater than to red and to yellow, and since so large an increase in the energy value of the stimulus made no detectable difference in the limits and any further increase lessened rather than increased the chromatic component of the response, it seems highly improbable that the limits could by any means whatsoever be extended the 20 to 35 degrees needed to make them co-extensive with the limits of white light vision. It seems fairly certain, therefore, that while the far periphery of the retina is only deficient in its chromatic sensitivity to red, yellow and blue, the blindness to green is absolute.

(2) In the investigation of the effects of changes of intensity on the limits of sensitivity eight intensities were used, sustaining to each other the following relations: 1, ½, ¼, ⅛, 1/16, 1/32, 1/64 and 1/128. The highest intensities were taken respectively from the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current and from a spectrum made equal in energy to the blue of this spectrum. These spectra will be designated as Spectrum A and Spectrum B. The reductions were produced by means of an aluminum sectored disc of 180, 90, 45, etc., degrees open

sector. The energy values of the different intensities of light, as has already been stated, were obtained by radiometering the highest intensities and computing the lower from the simple law of the disc. It had been our intention to make the investigation systematically with the eight different intensities in the sixteen meridians of the retina. However, for the purpose of the present paper, a briefer substitute plan has been adopted. A preliminary investigation was made with the eight intensities of Spectrum A in two meridians of the retina, the nasal and the temporal—which meridians represent opposite extremes with regard to breadth of zone of sensitivity—in order to get some idea of the amounts of reduction that would be needed to be effective in changing the limits. It was found, for example, that a reduction of the red light to $\frac{1}{32}$ of its value at intensity A was not sufficient to narrow the limits in the nasal and temporal meridians, the meridians designated in the tables and charts as 90 degrees. At this value the stimulus was still slightly supra-liminal in these meridians at the limits of white light vision. This amount of reduction, however, was sufficient to narrow the limits for the other stimuli by quite considerable amounts. Also a further investigation showed that it was enough to narrow the limits for red in 12 out of the 16 meridians employed. It was decided, therefore, to made the final determinations in the 16 meridians with the full intensities A and B and with $\frac{1}{32}$ A and B. The amount of narrowing for the yellow of the prismatic spectrum in the different meridians produced by this reduction ranged from 3 to 11 degrees; for the green, from 5 to 17 degrees; for the blue, from 10 to 18 degrees; and for the red, from 0 to 8 degrees. For the equal energy spectrum the amount of narrowing for the yellow ranged from 5 to 18 degrees; for the green, from 5 to 15 degrees; for the blue, from 4 to 18 degrees, and for the red from 3 to 25 degrees.

(3) In case of the equal energy spectrum of the higher intensity, all of the lights with the exception of the green

were seen in their proper color to the limits of white light vision in each of the 16 meridians. Made equal in energy to the blue of the prismatic spectrum (882.025×10^{-10} watt) the red and yellow were considerably less in energy value than was the green of that spectrum. Still the red and yellow were sensed to the limits of white light vision while the green, which represented a considerably greater amount of energy, fell short of those limits by amounts varying from 20 to 35 degrees in the different meridians. There can be no reasonable doubt, we believe, that the difference found here represents an actual difference in sensitivity. It obviously cannot be attributed to the relative intensities of the stimuli employed.

Landolt also has investigated the effect of high intensities on the extension of the limits of sensitivity. Writing of this work,[4] he says, "In ein absolut dunkles Zimmer fiel nur durch eine kleine Öffnung in Finsterladen directes Sonnenlicht. Dieses wurde auf das ausserste Ende des Perimeterbogens gelenkt. Während wir unser Auge ins Centrum des Bogens setzen, bracht man in die kleine, intensive beleuchtete Stelle farbige Papiere von möglichster Intensität der Färbung. Nun bewegtet sich das Auge langsam von entgegengesetzen Ende des Bogens nach Scheitelpunkte zu und es zeigte sich dabei, dass wenigstens mit der innern Netzhautpartie alle Farben schon bei 90° erkannt wurden. Die Grösse des Objectes betrug weniger als 1 cm.

"Als dieselben Prüfungen auch mit Spectralfarben zu machen, entwarfen wir ein Sonnenspectrum im sonst dunkeln Zimmer und liessen es durch eine achromatische Linse auf einen Ende des Perimeters befindlichen Schirm fallen. Dieser hatte eine verändliche Spalte, mittelst welcher man die einzelnen Farben aus dem Spectrum isolieren konnte. Während wir nun wiederum nach länger Adaptation, und bei verbundenem zweiten Auge das eine Ende des Bogens fixierten, würde von einem Assistenten irgendeine Farbe des Spectrums auf die Spalte gelenkt, und wir drehten nun, unter stehter Fixation underer Fingerspitze, welche sich auf dem Bogen bewegte, das Auge allmählig der Farbe entgegen. Es zeigte sich auch hier wiederum dass alle Farbe schon bei 90° erkannt werden, wenn sie intensiv genug sind."

Landolt's investigation was made, it will be noted, in a dark room while ours was made in a light room. We have not as yet had opportunity to repeat the work of the present paper with the dark adapted eye. However, determinations somewhat rougher and less detailed than those described here have sufficed to show that for our observers the far periphery of the retina is blind to green also with the dark adapted eye. With reference to the relative insensitivity of the peripheral retina to green, it may further be noted that in our results with the Hering papers with a different set of observers the limits for green fell much nearer to the center of the retina than for red, yellow and blue. The results represented in Figure V, for example, were taken from this series of observations. That the limits for green are narrower than for red, yellow and blue with stimuli of the same order of intensity has, moreover, been verified many times in the work of our undergraduate laboratory.

In Table I, (A) are given the results of the preliminary investigation in the nasal and temporal meridians to find out whether an intensity of light may not be gotten sufficiently high to make the limits of color sensitivity coincide with the limits of white light vision, and once this intensity is attained how much reduction is needed to produce a significant narrowing of the limits. We have already indicated in this and in previous papers the large changes of intensity that are needed to change the limits by a significant amount when a certain degree of excentricity has been reached. How very large these changes have to be for the far periphery of the retina is shown in this table.

In Table I, (B) is given a specification of the energy values of the stimuli used in making the determinations represented in Table I, (A). Four energy values may perhaps be considered of importance for each determination: the total value

TABLE I

A. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Prismatic Spectrum.

In this table are given the results of a preliminary investigation in two representative meridians to show how much reduction is needed to produce a significant change in the limits of sensitivity. Eight intensities of stimulus were used: A, ½A, ¼A, ⅛A, etc.

		Limits of Sensitivity for							
Meridian Investigated	Stimulus	Intensity A	Intensity ½A	Intensity ¼A	Intensity ⅛A	Intensity $\frac{1}{16}$A	Intensity $\frac{1}{32}$A	Intensity $\frac{1}{64}$A	Intensity 1/128A
Nasal	Red (670μμ)	92	92	92	92	92	92	88	86
	Yellow (581μμ)	92	92	92	92	91	89	88	88
	Green (522μμ)	69	69	69	66	63	62	59	56
	Blue (468μμ)	92	92	87	83	79	78	77	76
Temporal	Red (670μμ)	61	61	61	61	61	61	46	44
	Yellow (581μμ)	61	61	61	61	55	47	46	45
	Green (522μμ)	45	45	45	42	34.5	32.5	30	29
	Blue (468μμ)	61	61	56	45	43.5	43	43	43

B. The Energy Values of the Stimuli Used.

Total energy of light at campimeter opening and at eye (watt$\times 10^{-10}$)

Intensity	Red (670μμ)	Yellow (581μμ)	Green (522μμ)	Blue (468μμ)
A *	9096.639	4065.624	1562.388	822.025

* The energy values of ½, ¼, ⅛, $\frac{1}{16}$, $\frac{1}{32}$, $\frac{1}{64}$, and 1/128A may be obtained by dividing the above values by the appropriate factor.

The energy density at the campimeter opening (watt per sq. mm.) may be obtained by multiplying the above values by 0.005659; the energy density at the eye by multiplying them by 0.303.

at the campimeter opening, the density per sq. mm. at the campimeter opening, the total energy entering the eye, and the density per sq. mm. at the eye. For the sake of brevity, however, only one of these values is given in the table; namely, the total energy entering the eye. The factors needed to convert this value into density at the eye and at the campimeter opening are appended in a footnote. Since all of the light from the campimeter opening is focussed into the image on the pupil, the figures expressing the total energy at the eye and at the campimeter opening are the same. The most important of the four specifications noted are probably the total amount of light entering the eye and the density at the campimeter opening. The latter value, for example, sustains a fixed but unknown ratio to the density of the image formed on the retina.

In Table II are given the brightness values of the pre-exposure and campimeter screen for the work represented in Table I, (A). As stated earlier in the paper, the pre-exposure and the campimeter screen were selected from the Hering series of standard papers. In case of the higher intensities of light used, No. I of this series (the standard white, coefficient of reflection about 75 per cent) reflecting the light of the room was not as bright as the stimulus light. These cases may be identified in this and the following tables by the brightness value of this paper under the illumination of the room; namely, 0.05088 c. p. per sq. in.

In Table III are given the limits of sensitivity in 16 meridians of the retina for the highest intensity of light used for the work represented in Table I, intensity A, and also for $\frac{1}{32}$ A, an intensity representing the order of reduction needed for all of the colors to produce any considerable narrowing of the limits at the extreme periphery of the retina. The 16 meridians used are designated as follows: The upper vertical meridian is marked 0 and the lower vertical, 180 degrees. Beginning with 0 and reading down to left or right

TABLE II

In this table are given the brightness values of pre-exposure and campimeter screen in candle power per square inch * for the determination of limits given in Table I. In all cases in which it was possible, the brightness of the pre-exposure and campimeter screen was made equal to that of the stimulus at the limits of sensitivity.

Brightness Value of Pre-exposure and Campimeter Screen

Meridian	Stimulus	Intensity A	Intensity ½A	Intensity ¼A	Intensity ⅛A	Intensity $\frac{1}{16}$A	Intensity $\frac{1}{32}$A	Intensity $\frac{1}{64}$A	Intensity 1/128 A
Nasal	Red (670$\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.03093	0.02116
	Yellow (581$\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.03663	0.02686
	Green (522$\mu\mu$)	0.05088	0.05088	0.05088	0.03663	0.03663	0.02686	0.02116	0.01384
	Blue (468$\mu\mu$)	0.05088	0.05088	0.03663	0.02686	0.01262	0.01140	0.00643	0.00578
Temporal	Red (670$\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.03093	0.01791
	Yellow (581$\mu\mu$)	0.05088	0.05088	0.05088	0.05088	0.05088	0.05088	0.02686	0.02116
	Green (522$\mu\mu$)	0.05088	0.05088	0.05088	0.03663	0.02686	0.01384	0.01140	0.01140
	Blue (468$\mu\mu$)	0.05088	0.05088	0.03663	0.03093	0.01262	0.01140	0.00716	0.00643

* The above values may be converted into millilamberts by multiplying by 486.8

they are 0, 25, 45, 75, 90, 110, 135, and 180 degrees. The specification of the energy of the stimuli at intensity A and $\frac{1}{32}$A are given, it will be noted, in Table 1,(B). For all of the stimuli at intensity A, No. 1 of the Hering series of papers was used as pre-exposure and campimeter screen, as has already been noted. This paper illuminated by the light of the room was too dark (0.05086 c. p. per sq. in.) for all of the four colors at the limits of sensitivity. However, for the want of a suitable pigment surface of higher reflection coefficient it was used. For intensity $\frac{1}{32}$ A, it was darker than the yellow stimulus and approximately equal to the green and red. For the blue stimulus Nos. 9 to 14 of the Hering series (0.01404–0.0114 c. p. per sq. in.) were used as needed in the different meridians. The photometric values for these intensities and intensity B and $\frac{1}{32}$ B have not been given in detailed tabular form because of the large number of repetitions that occur.

TABLE III

The Effect of Intensity of Stimulus on the Limits of Sensitivity, Prismatic Spectrum.

In this table are given the limits of sensitivity in 16 meridians of the retina for intensity A and $\frac{1}{32}$ A of Table II. The upper vertical meridian is numbered 0° and the lower vertical 180°. Reading down to right or left they are 25°, 45°, 70°, 90°, 110°, 135°, 155°, and 180°.

Meridian Investigated	Limits of Sensitivity for							
	Intensity A				Intensity $\frac{1}{32}$ A			
	Red (670μ μ)	Yellow (581μ μ)	Green (522μ μ)	Blue (468μ μ)	Red (670μ μ)	Yellow (581μ μ)	Green (522μ μ)	Blue (468μ μ)
Nasal								
0°	65	65	36	65	64	57	29	50
25°	86	86	49	86	83	79	36	72
“ 45°	90	90	52	90	89	83	38	76
“ 70°	92	92	67	92	92	86	59	77
“ 90°	92	92	69	92	92	89	62	78
“ 110°	91	91	68	91	90	87	59	78
“ 135°	88	88	61	88	87	84	49	75
“ 155°	86	86	47	86	84	78	35	67
“ 180°	57	57	36	57	53	47	27	42
Temporal								
25°	65	65	44	65	64	55	31	52
“ 45°	65	65	50	65	57	56	33	51
“ 70°	62	62	46	62	55	50	35	44
“ 90°	61	61	45	61	61	47	32.5	43
“ 110°	58	58	37	58	57	49	31	48
“ 135°	55	55	32	55	55	48	27	40
“ 155°	54	54	30	54	50	43	25	41

In Table IV, (A) are given the limits of sensitivity in 16 meridians of the retina for the four stimuli all made equal in energy to the blue used in Table I and for $\frac{1}{32}$ of this value. These values are, as we have already indicated, designated in the table as intensity B and $\frac{1}{32}$ B. In Table IV, (B) are given the energy values of the stimuli used for Table IV. For the higher intensity of these stimuli, intensity B, No. 1 of the Hering series of papers (0.05088 c. p. per sq. in.) was used for the pre-exposure and campimeter screen. Again

TABLE IV

A. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Equal Energy Spectrum.

In this table are given the limits of sensitivity in 16 meridians of the retina for stimuli all made approximately equal in energy to the blue of the prismatic spectrum used in Table I, and for $\frac{1}{32}$ of this intensity,—Intensity B and $\frac{1}{32}$ B.

Meridian Investigated	Limits of Sensitivity							
	Intensity B				Intensity $\frac{1}{32}$ B			
	Red (670μ μ)	Yellow (581μ μ)	Green (522μ μ)	Blue (468μ μ)	Red (670μ μ)	Yellow (581μ μ)	Green (522μ μ)	Blue (468μ μ)
Nasal								
0°	65	65	34	65	62	56	29	50
“ 25°	86	86	47	86	74	70	34	72
“ 45°	90	90	50	90	74	78	36	76
“ 70°	92	92	63	92	78	85	50	77
“ 90°	92	92	69	92	81	87	59	78
“ 110°	91	91	64	91	79	85	58	78
“ 135°	88	88	44	88	74	80	42	75
“ 155°	86	86	36	86	61	74	32	67
“ 180°	57	57	31	57	46	39	25	42
Temporal								
“ 25°	65	65	38	65	57	54	30	52
“ 45°	65	65	39	65	47	55	32	51
“ 70°	62	62	42	62	46	48	30	44
“ 90°	61	61	41	61	40	45	30	43
“ 110°	58	58	36	58	45	45	29	48
“ 135°	55	55	28	55	49	41	25	40
“ 155°	54	54	26	54	47	38	24	41

B. The Energy Values of the Stimuli Used.

Total energy of light at campimeter and at eye (watt × 10^{-10})

Intensity	Red (670$\mu\mu$)	Yellow (581$\mu\mu$)	Green (522$\mu\mu$)	Blue (468$\mu\mu$)
B *	891.050	882.510	884.946	882.025

* The energy value of $\frac{1}{32}$ B may be obtained by dividing the above values by the appropriate factor.

The energy density at the campimeter opening (watt per sq. mm.) may be obtained by multiplying the above values by 0.005659; the energy density at the eye by multiplying them by 0.303.

it was darker than all of the four colors at the limits of sensitivity. For intensity B it was slightly darker than all of the four colors at the limits of sensitivity. For intensity $\frac{1}{32}$ B it was slightly darker than the yellow. For the green of this intensity the No. 2 gray of this series was used (0.0366

c. p. per sq. in.); for the red, Nos. 10 to 14 (0.01384 – 0.0114 c. p. per sq. in.) varying for the different meridians, and for the blue, Nos. 7 to 14 (0.0171 – 0.0114 c. p. per sq. in.).

Graphic representations of the results of Table III are given in figures 1 and 2. In figure 1 are shown the limits of sensitivity to the four stimuli in the 16 meridians for the intensities represented in the prismatic spectrum A. The limits for the red, yellow and blue stimuli at this intensity are, it will be remembered, coincident with the limits of white

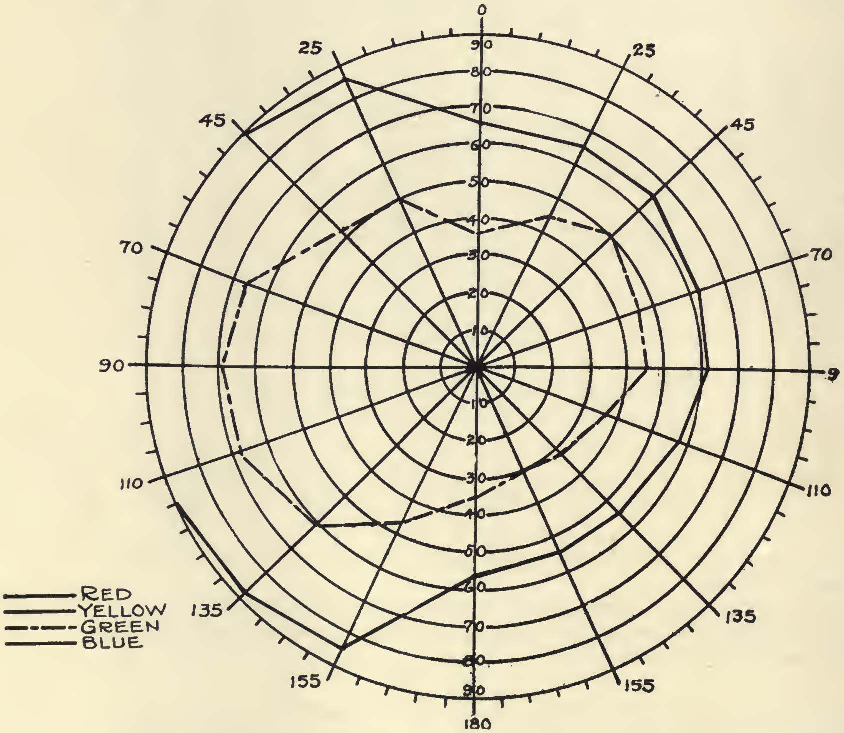

Chart 1. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Prismatic Spectrum.

In this chart are represented the limits of sensitivity for intensity A of Table I: red 9096.639, yellow 4065.624, green 1562.388, and blue 882.035 $\text{watt} \times 10^{-10}$.

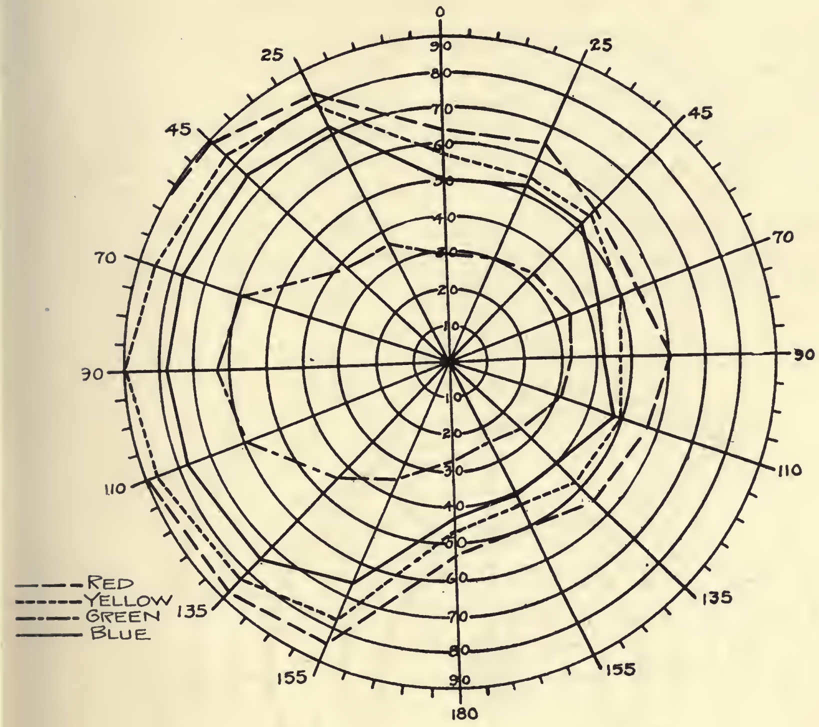

Chart 2. The Effects of Intensity of Stimulus on the Limits of Sensitivity, Prismatic Spectrum.

In this chart are represented the limits of sensitivity for intensity $\frac{1}{32}$ A of Table II: red 234.27, yellow 127.051, green 48.825, and blue 27.563 watt $\times 10^{-10}$.

light vision. All four limits may be represented, therefore, by a single tracing, an unbroken line in black. The limits for green are represented by a broken line. In figure 2 are represented the limits of sensitivity for the four stimuli at the intensities represented in the prismatic spectrum, $\frac{1}{32}$ A. In this case the zone of sensitivity to blue is outlined by an unbroken line and the zones for the other colors by broken lines as indicated in the figure. An inspection of this figure will show that the degree of excentricity of the limits is in the order of the intensity of the stimuli. In discussing the significance of the criss-crossing or interlacing of the limits obtained with the Hering pigment papers in previous work, it is to be noted that this is what was pointed out would occur if there were a significant difference in the intensity of the stimuli. That is, if the zone of sensitivity to red, for example, is in one meridian wider and in another narrower than to green, etc., it cannot be due to any difference in the intensity of the stimuli; for such a difference, if significant, would

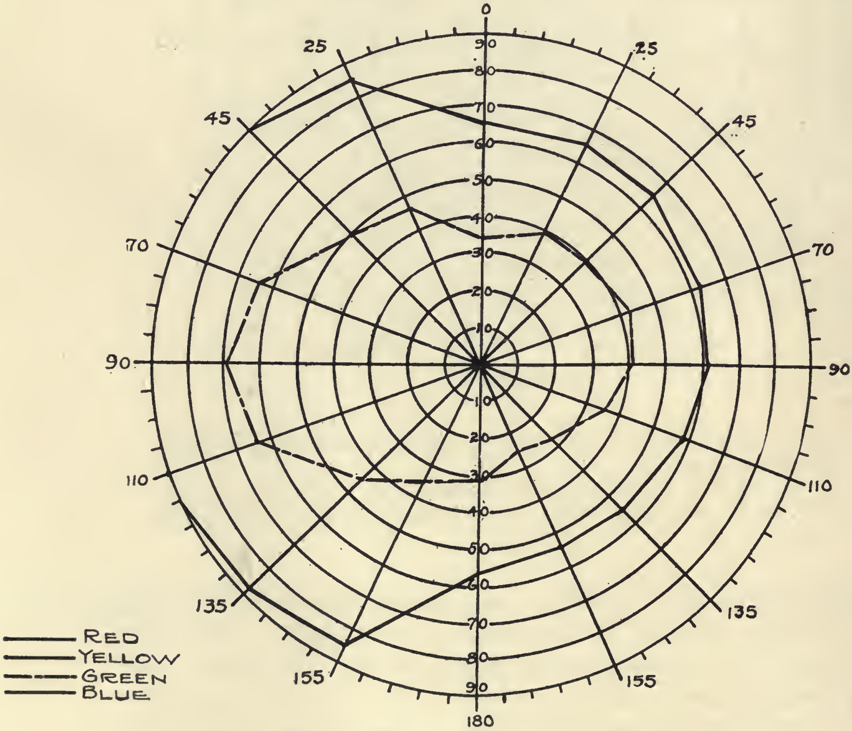

Chart 3. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Equal Energy Spectrum.

In this chart are represented the limits of sensitivity for intensity B of Table IV: red 891.05, yellow 882.51, green and blue 882.025 watt × 10^{-10}.

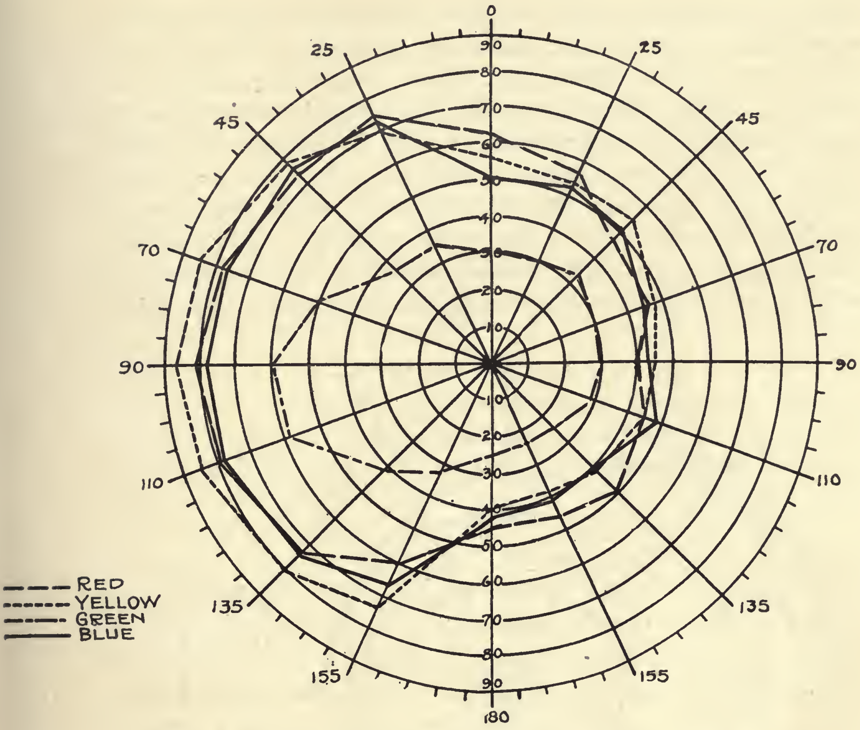

Chart 4. The Effect of Intensity of Stimulus on the Limits of Sensitivity, Equal Energy Spectrum.

In this table are represented the limits of sensitivity for intensity $\frac{1}{32}$ B of Table IV: red 27.845, yellow 27.578, green 27.655, and blue 27.563 watt × 10^{-10}.

make one zone consistently wider or narrower than the other in all meridians.

A graphic representation of the results of Table IV is given in figures 3 and 4. In figure 3 are shown the limits of sensitivity to the four stimuli in the 16 meridians for the intensities represented in the equal energy spectrum B. Again the limits for the red, yellow and blue stimuli coincide with the limits of white light vision and are represented by a single tracing, the unbroken line in black. The limits for green are represented by a broken line. In figure 4 are shown the limits for the four stimuli at the intensities represented in the equal energy spectrum $\frac{1}{32}$ B. With regard to this figure, the following points may be noted. (1) With stimuli of equal energy the limits of no one of the colors, red, yellow and blue, are consistently wider than the others. That is, their limits are characterized by frequent criss-crossing or interlacing. The limits for all three colors, however, are consistently wider than for green. And (2) figure 4 sustains a somewhat

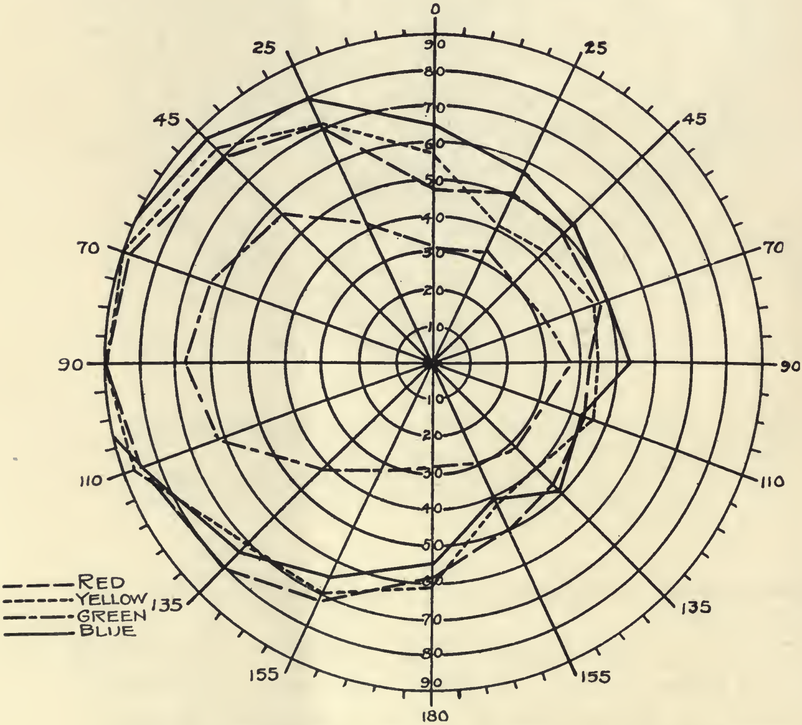

Chart 5. The limits of sensitivity to red, yellow, green and blue of the Hering Series of pigment papers, intensity of illumination, vertical component, 390 foot-candles.

striking general similarity to the charts obtained for the Hering pigment papers. One of these showing the limits with a surrounding field and pre-exposure of the brightness of the colors employed is given in figure 5. While no conclusion can be drawn from this similarity with regard to the relative energies of the wave-lengths dominantly reflected by these papers, still it suggests that they may all, roughly speaking, be somewhere near the same order of value, at least much more nearly so than are these colors in the prismatic spectrum. The red, yellow, green and blue of the prismatic spectrum gave, it will be remembered, rather widely concentric, not criss-crossing limits.

In this general connection it may be of interest also to note the close correlation which obtains between the results of this investigation and those of the previous investigation of the sensitivity of the peripheral retina by the threshold method. That is, wherever the thresholds are found to be low the limits are found to be wide and conversely, wherever the thresholds are high the limits are found to be correspondingly narrow. Some interesting results follow from this. For example, in a given meridian the threshold curve for a given color is found to be very irregular, rising in some places slowly, in others quickly, and still in others dropping and rising again. These fluctuations in the curve are, moreover, different in the different meridians. This means, of course, that the shape of the zones of sensitivity for this color should change with the intensity of the stimulus employed, which is found to be the case. Furthermore, in the same meridian the threshold curves for the different colors differ from each other widely in the direction and amount of the irregularity; and this difference in turn varies from meridian to meridian. The result of this is that a criss-crossing or interlacing of limits must take place whenever stimuli of such relative intensities are used that the limits are of the same general order of excentricity. In other words, as was pointed out in our discussion of this phenomenon in earlier papers, criss-crossing can mean only that there is a lack of uniformity in the relative sensitivity to the different colors in the different meridians. For example, when it occurs in the limits for blue and yellow, it indicates that the ratio of sensitivity to blue and yellow changes in passing from meridian to meridian. In short, any investigation at all comprehensive either of the thresholds or limits of sensitivity shows that striking irregularity and not uniformity characterizes the distribution of chromatic sensitivity in the peripheral retina. This is in direct opposition, it will be remembered, to the claim made by Hess [5] that constancy of ratio of sensitivity to the paired colors prevails throughout the retina, which claim it will be remembered was advanced by Hering [6] in support of his own theory and in refutation of the Fick [7] and Leber [8] modifications of the Helmholtz theory to explain the color-blindness of the peripheral retina. So far as we are able to determine no one intensity or set of conditions will give coincidence of limits in all meridians for any two colors inside the limits of white light vision.

The bearing of these results on the work of the clinic may be indicated in part as follows. In the practice of perimetry as applied to diagnosis it is commonly accepted that the field of vision for the normal eye may be divided concentrically in the following order: white light and form, blue, red and green. It is obvious from the foregoing results, (a) with stimuli taken from the prismatic and equal energy spectra and (b) from the effects obtained by varying the intensity of the stimuli, that the responsibility for such a rating of the color fields rests for the greater part with the relative intensities of the pigment stimuli used in the work of the clinic. That is, the limits of sensitivity to red, yellow, blue and white light for stimuli of high intensities are coincident; for stimuli of lower intensities taken from the prismatic spectrum they are rather widely concentric; and for stimuli of equal energies of the order of intensity, roughly speaking, represented by the pigment stimuli they are interlacing.

Another feature of interest is the claim that has been made by certain clinicians but not generally accepted, we believe, that the interlacing of the limits for blue and red indicates a pathological disturbance in the relative distribution of sensitivities. While we are not disposed to dispute this conclusion because of a too meager knowledge of all of the data that should be taken into consideration in its evaluation, still we do think it fair to note that pathological disturbances are only one set of factors that may contribute to such a result and that widely different results may be gotten with the same eye with no greater difference in the test conditions than may occur from time to time in the same clinic or laboratory unless a clear understanding is had of the factors which affect the apparent powers of response of the peripheral retina and adequate means are exercised for their control. These factors are, as we have already indicated, the wave-length and purity of the stimulus, intensity of stimulus and visual angle, length of exposure of the eye, accuracy and steadiness of fixation, the general illumination and state of adaptation of the retina, breadth of pupil, and brightness of pre-exposure and surrounding field. The most potent of these is intensity of the stimulus.* The equable control of this factor seems to have presented considerable difficulty in the work of the laboratory and clinic when pigment surfaces have been used as stimuli. In perimetry, for example, with a given set of pigment stimuli the intensity of the stimulus light is determined by the intensity of the illumination of the perimeter arm at the different points of exposure, which is apt to be very irregular. The control of the illumination of the perimeter has also another important effect. Unless it is kept constant and uniform for all points on the perimeter arm in all of its positions, the effect of brightness of pre-exposure and surrounding field cannot be eliminated, *i.e.*, the shade of gray which is needed to match the color in brightness changes with change of illumination (the Purkinje phenomenon). With the methods of illuminating the perimeter and campimeter at present employed in office and clinic work there is little chance of having either uniformity of illumination of the stimulus and its background at every point in the field of view or of maintaining its constancy from time to time, from clinic to clinic, or even throughout a single set of determinations. Obviously, if the determination of the apparent limits is to be given diagnostic significance, the work should be done under conditions which have been carefully standardized with reference to all of the factors which affect the power of chromatic response, for the apparent limits are a resultant of these conditions as well as of the actual distribution of sensitivities.

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*This control of the intensity of the stimulus has been secured for daylight work in our own investigations by means of a specially designed optics room and rotary campimeter.[9] Neither of these refinements is available for office and clinic work. We have devised, however, and are having constructed a perimeter by means of which equal illumination of the stimulus with artificial light approximating daylight in composition is secured at every point on the arc and the variable effects of brightness of pre-exposure and surrounding field can be eliminated with an ease and convenience of manipulation which, we believe, is feasible for office and clinic work.

The degree of importance that is attributed by at least one clinician to the absolute and relative distribution of sensitivities over the retina may be indicated by the following quotation from a recent work on perimetry. "Contraction of the form fields shows the degree of disease of the visual tract. It is better evidence of the real condition of the visual path than an ophthalmoscopic study can possibly furnish. The evidence is minute and analytical. The color fields and color changes moreover furnish a more delicate test in the early stages of the disease and at times furnish a clue to the seat of the trouble before an appreciable change has taken place in the form field."[10]

Summary of Results and Conclusions

The more significant features of the above results may be summarized briefly as follows:

(1) The far periphery of the retina is not blind to red, blue and yellow. It is merely deficient in sensitivity to these colors. That is, with stimuli of sufficient intensity the limits of red, blue and yellow coincide with the limits of white light vision. The blindness to green, however, is for our observers absolute.

(2) The amount of change of intensity required to produce a detectable change in the apparent limits of sensitivity in the more remote parts of the retina is very great. This amount changes very irregularly from center to periphery of the retina in a given meridian and from meridian to meridian as might be expected from the great irregularity in the distribution of sensitivity in the peripheral retina. (cf. The Chromatic Thresholds of Sensitivity from Center to Periphery of the Retina and their Bearing on Color Theory, *Psychological Review*, 1919, XXIV, pp. 16–42.)

(3) Two other important phenomena may also be mentioned as a result of this irregularity. (a) The shape of the zone of sensitivity to a given color changes with the intensity of the stimulus employed in making the determination. And, (b), when stimuli of equal or of the same order of intensity are used the limits for red, yellow and blue are found to interlace or criss-cross each other irregularly rather than to coincide in complementary pairs as was reported by Bull, Hegg, Hess and Baird, in a more limited investigation of the retina's powers of response. The former phenomenon is the direct corollary of the difference in the rate of decrease of sensitivity to a given color in passing from the center to the periphery of the retina in the different meridians; the latter, to the change in the ratio of sensitivity to the different colors from meridian to meridian. The lack of uniformity of grad-

ing of function from point to point in the periphery of the retina, reported in this and previous papers, while striking, can scarcely be considered as surprising. It is in fact just what might be expected of those parts of a sense organ which are little used and poorly developed.

(4) The responsibility of the accepted clinic rating of limits in the order from widest to narrowest of blue, red and green doubtless for the greater part rests with the relative intensities of the pigment stimuli used in the work of the clinic. With stimuli of high intensity the limits for red, yellow and blue coincide with the limits of white light vision; for stimuli of lower intensities, taken from the prismatic spectrum, they are rather widely concentric; and for stimuli of equal energies of the order of intensity represented by the pigment stimuli they are interlacing.

(5) The interlacing of limits for red and blue is a normal result for stimuli of equal energy of medium intensities. It may not, therefore, be due to pathological disturbances in the distribution of sensitivities as has been claimed by certain clinicians. In all responsible work on the determination of the apparent limits it is obviously of great importance to bear in mind that the results are dependent both upon the actual distribution of sensitivity and the numerous factors which affect the apparent powers of response of the peripheral retina.

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Editorials

How Bright are the Stars and Why is the Sky Blue?

THE brightness of the stars on a clear night and the blueness of the sky on a clear day have been objects of wonderment to children and scientists alike. Each in his own way has wondered about these marvels of the firmament. Of course the poet, who rhymes for all kinds of children, has sung of the stars and the sky to his heart's content.

Just recently someone has taken the data on the brilliancy and parallax of a variety of stars and from these the light of the star as compared with that of the sun has been computed, assuming the stars at the same distance from the earth as is the sun. We are told that the brightness of the sun as compared with Sirius is 36, Arcturus 832, Pollux 83 and so on. And again, it has been found that the illumination per degree square of the region containing the Milky Way is about twice that of the regions outside it.

Fabry has put forward the theory that the production of the morning and evening sky colors depends upon diffuse reflection of light from a layer of discontinuity such as the stratasphere. For he considers that diffraction alone is insufficient to account for the phenomena. English investigators have been able to devise laboratory experiments to show that there is a scattering of light by dust-free air. This would account almost completely for the luminosity and the blue color of the sky on very clear days and at considerable altitudes above sea level. Air being taken as a standard, it has been found that hydrogen gas gives less scattering than air, oxygen about the same, carbon dioxide decidedly more, but the scattered light in all cases was the same as that which we say constitutes the blueness of the sky. All results are therefore in qualitative agreement with the theory that the blueness of the sky is due to the scattering of light by the molecules of air and not by dust particles in it as has been commonly taught.

Some Recent Conclusions upon Retinal Characteristics

SELF-LUMINOUS preparations, such as those employed to make metal dials luminous, have been recently used in an instrument devised to test minimum light sense and retinal adaptation. A series of buttons, specially prepared and mounted around a disc, are picked so that they have the same luminous intensity as determined by photographic values. The intensity of the luminous energy radiated from these equally intense lights is regulated by a difference in the number of layers of white celluloid covering various buttons. This intensity is then made to vary from a minimum to the maximum. These discs can be observed through an eyepiece.

Recent experiments have shown that equal quantities of light may determine widely different quantitative impressions on the retina according to the method of striking it. These impressions are much greater when the light gradually increases to a maximum than when it starts off quickly with the maximum intensity. The effect is not the same for all wave-lengths. The name "retinian inertia" has been given these phenomena.

It has been known for some time that electrical changes go on in the eye when the retina is exposed to light. During the year 1919 experiments were reported in which the effects of various colors upon this retinal reponse were investigated. It was found that relatively positive and negative potentials were established by different wave-lengths and that the excessive action of a given monochromatic radiation would promote the subsequent action of its complementary.

The phenomenon of the persistence of vision has been employed to determine, if possible, the number of fundamental color sensations and the precise wave-lengths by which they are excited. The experimental results are interpreted by Allen as supporting four transition points and hence the theory of three primary sensations—red, green and violet— and two compound sensations, yellow and blue. Also, other tests upon the persistence of vision made by other experimeters have shown that this phenomenon is a maximum at the macula and diminishes from this point to the periphery.

Color blindness is the title of a bulletin of the *United States Public Health Service.* Results of the tests upon one thousand persons are reported. The conclusion is reached that "color blindness is best detected by testing with color lights of known spectral composition." About nine per cent of men and two per cent of women among healthy individuals are color-blind. This color blindness is of a degree sufficient to be dangerous in occupations requiring recognition of colored signal lights in about three per cent of men and one-half of one per cent of women."

On Tinted and Colored Glass

A NUMBER of investigations have been made in the past year or two upon the transmission of various colored glasses used in commercial and ophthalmic work. These investigations have been reported in papers by Coblentz, Luckiesh, Gage, Ham, Emerson, McNicholas, Sheard and Smith. A few of these writers have given rather complete data on the transmission in the infra-red and the ultra-violet regions. In a general way the conclusion is reached that light neutral tints and shades of red and yellow glasses do not markedly influence the absorption of the infra-red, but that glasses which are strongly absorptive in the long wave-length region of the visible spectrum are more pronounced and efficient absorbers of infra-red radiation. The data now available upon these different glasses makes it possible to so combine glasses as to transmit narrow spectral regions of high intensity.

The effect of temperature on the transmission of colored glasses has been measured for a number of typical cases and it has been found that in going from a temperature of 30 degrees to 350 degrees C. the transmission factor was decreased in every instance (except that of a light blue glass) by amounts varying from 7 to 58 per cent. In the case of the blue (cobalt) glass the transmission factor was increased. The relation between temperatures and transmission factors has been found to be a straight line, approximately.

Transmission factors for several representative slightly diffusing glasses similar to those commonly used for office doors, skylights and such purposes, have been obtained under two conditions of illuminations: first, a narrow beam of light in a direction perpendicular to the surface of the specimen and second, uniformly diffused light reaching the specimen from all directions above its plane. The transmission factor is, in general, less for the diffused illumination than for the direct beam illumination. And again, for a glass having a rough and smooth side, the transmission was found to be considerably greater when the rough surface faced the light source. This phenomenon is apparent visually when so-called ribbed glass is used, but also exists with frosted and etched glasses.

Various experiments have recently been carried out with respect to the use of selenium as a decolorizer in glass manufacture. The glasses thus decolorized are classed as more brilliant than those in which manganese or nickel oxide is used. The selenium, when added as a decolorizing agent, evidently breaks up into very minute particles which causes a red color thereby neutralizing the faint green caused by the presence of iron.

Bright sunlight has an action in the nature of a colorizing effect upon glasses in general. Prolonged exposure to sunlight causes glasses decolorized by selenium to assume a brownish tinge. A writer in the *Illuminating Engineer* (London) 1918 has proposed as a "constructive use of a destructive process" the utilization of the action of ultra-violet light which causes the decolorizing of lamp globes and many other tinted glasses to produce new color effects in glasses and analogous substances such as porcelains, quartz and some of the semi-precious stones. Investigations along these lines indicate no physical change other than that of color. In fact, the actual colors may be considerably changed without greatly affecting the transmission percentages of various regions of spectral energy. In other words, the foregoing statement leads us to conclude this editorial with the remark that color *per se* is not a safe indicator of probable absorption or transmission. Ambers of the same tint vary enormously in the limits of transmission in the short wave-length region as well as in percentages of energy transmitted in the visible region.

How Do the Blind See?

NOT so many weeks ago our fancy led us to pick up and re-read a little volume by Javal which he chose to entitle "On Becoming Blind"—written originally in French and admirably translated for us by Dr. C. E. Edson (Macmillan Co., 1905). There is something fascinating and yet heart-touching in the captions of the chapters: for who, but one who had lost his sight, would think of discussing such everyday topics as household occupations, meals, watches and clocks, walking in town and country, music, games, tobacco. The contrast of associations in a world once seen with the physical and mental eyes of such a man as Javal as compared with those impressions gathered only through other faculties is most painstakingly recorded. To be sure physiological optics has to do with vision and not its opposite. And yet, one of the greatest of ophthalmic scientists—

the joint designer with Schiötz of the ophthalmometer bearing their names, the author of a classic treatise on *Strabismus*—belabors all his "oculist confrères" for their failure to prepare their patients for the "leap in the dark." For, he says, "to give by a placebo treatment consolation to an incurable is to prevent him from arranging his life in anticipation of the fatal outcome. It seems to me more humane to do for the blind what I wish had been done for me and to prepare them little by little for their fate. If, for example, you foresee that the patient will one day be forced to resort to Braille writing, is it not a duty to use the little sight left him to teach him the first elements of this process?"

So in the twenty-fifth chapter of his brochure Javal writes of the *Sixth Sense*, only to immediately remark that it may not exist. The blind see, but how? By the "sense of obstacles"? Certain it is that many completely blind persons have this sense of obstacles highly developed. Blind children play without bumping into obstacles, they appear to recognize the presence of windows and doorways and can sense whether they are open or shut. Quite commonly the blind assert that the seat of sensation lies in the forehead. Others attribute the sense of an obstacle to air pressure. But the perception is sharper when they slowly approach the object which gives them the knowledge of its presence through the facial sensations. So-called mirages are experienced; false impressions of the immediate presence of an obstacle are received. Various explanations have therefore been advanced: some attribute this sensation of obstacles to auditory sensations, others do not allow the auditory sense any rôle in the process, others believe that the tympanum acts as a receptor without there being any auditory perception, while other blind people believe in and report simultaneous action of auditory and other sensations.

Javal cites the case of a professor of history at the National Institute of Paris who, at four years of age, lost his sight through atrophy of the optic nerves. Likewise he lacked the sense of smell. This professor enjoyed the "sense of obstacles" in a remarkable degree, being able to sense the presence of a wall less than eight feet away, to recognize a big piece of furniture in a room and so forth, but the sense of obstacles was lost in noisy surroundings. The sense of hearing was possibly at the botton of his sense of obstacles. In another case, that of a young man blind since the age of two years, the sense of hearing evidently revealed the neighborhood of obstacles, for the shaking of the leaves on the trees along the road and the deadening of his footsteps by the foliage or the presence of snow upon the ground destroyed this sense of obstacles.

One of the most interesting pieces of testimony is given by W. Hanks Levy in his work on *Blindness and the Blind* (London, 1872). Levy thus describes his faculty of perception:—"Whether within a house or in the open air, whether walking or standing still, I can tell, although quite blind, when I am opposite an object, and can perceive whether it be tall or short, slender or bulky. I can also detect whether it be a solitary object or a continuous fence; whether it be a close fence or composed of open rails; and often whether it be a wooden fence, a brick or stone wall, or a quickset hedge. I cannot perceive objects if much lower than my shoulder, but sometimes very low objects can be detected. This may depend on the nature of the objects, or on some abnormal state of the atmosphere. The currents of air can have nothing to do with this power, as the state of the wind does not directly affect it, as when snow lies thickly on the ground objects are more distinct, although the footfall cannot be heard. I seem to perceive objects through the skin of my face and to have the impressions immediately transmitted to the brain. The only part of my body possessing this power is my face; this I have ascertained by suitable experiments. Stopping my ears does not interfere with it, but covering my face with a thick veil destroys it altogether. None of the five senses have anything to do with the existence of this power, and the circumstances above named induce me to call this unrecognized sense by the name of facial perception. . . . . When passing along a street I can distinguish shops from private houses, and even point out the doors and windows, etc., and this whether the doors be open or shut. When a window is composed of one entire sheet of glass, it is more difficult to discover than one composed of a number of small panes. From this it would appear that glass is a bad conductor of sensation, or at any rate of the sensation specially connected with this sense."

Javal discusses the possibility that the sixth sense is due to heat perception, saying that there can be loss of heat sensation with the preservation of the tactile sense. A sensation of heat is experienced by our skin without its being in contact with a hot body. Embryologically the retina is related to the cutaneous epithelium. And as Javal points out, one may conceive that this epithelium in the frontal region might be lightly affected by a certain extension of the spectrum whose limits are not the same as the luminous spectrum. But, in the case of a teacher of the Perkins Institute of South Boston who possessed to a remarkable degree the ability of perceiving clouds—if we may be permitted the use of the word "perceiving"—it was found that his face did not possess a greater sensibility to heat than other persons.

The conclusion was apparently reached by Javal in some of his investigations that the "sense of obstacles" is the privilege of those born blind. But William James writes on this point as follows: "The membrana tympani is susceptible of noticing differences of pressure exerted by the external atmosphere, differences much too small to be possibly distinguished as a sound. After being seated and having the eyes closed, let the reader ask someone to bring silently before his face an object like a large book; he will at once have a consciousness of its presence as well as of its removal. A friend of the author, trying this for the first time, distinguished without hesitation the three degrees of thickness of a board, a trellis and a sieve held successively before his ear. Since they who never see make use of this sensation as a means of perception, we can admit that, for those whose attention is called to these phenomena for the first time, this appreciation is a quasi-sensation and owes nothing to the education of the senses. But what is perceived is very clearly and without denial the absence of limitation of space, quite as when lying on the back one perceives nothing but the blue and limitless extent of the sky. When someone brings an object to our ear, we at once experience a sense of imprisonment or shut-in-ness. If the object is suddenly taken away, it seems as if we were freed and in the presence of free space. And to whomsoever takes the trouble to try it, this sensation will be that of a vague appreciation of space."

From these remarks we may draw the conclusion that the blind see by sensations which are tactile and which are highly developed in that the tympanum acts as a receptor without there being any auditory perception.

In a general way it may be concluded with a fair degree of probability that the distance sense is a function of the sensitive nerves of the face, particularly the fifth nerve. Whether specific nerve fibers conduct this sensation or whether this occurs in the paths reserved for the senses of pressure and topography is still an open question.

May we not hope that further investigation will be made along these lines in order that the blind may be taught to perceive so that, though they have eyes that see not, yet may they be put in more intimate touch with the world outside of themselves.

The Interpretation of Dynamic Skiametric Findings

H. M. Bestor

SINCE the introduction of dynamic skiametry by A. J. Cross of New York in 1902, the writer has used it constantly in his practice. Over thirty thousand cases have been so examined of which over fifteen thousand cover a period since 1908.

During the entire time much has been written for and against this method of examination but no one, not even the author of the method, has given an entirely acceptable explanation of its working principles, its limitations and its interpretations.

Dynamic skiametry as suggested by Cross consists in having the patient read a series of test letters placed either on an examiner's brow attached to his skiascope, or to a fixation stand: then, by varying the accommodative demands as judgment teaches and by being able to easily supply artificial lens power, the accommodation is reduced to its normal relationship with convergence. Cross contends that no matter what the age of the patient, he will surrender only the accommodative excess which has been required to maintain near vision. This excess will therefore be composed of what has formally been called latent hypermetropia or tonic spasm.

As usually practiced, the fixation card is attached to the skiascope and used at a distance from half to a quarter of a meter from the eye under examination. The examiner using his mirror, checked up by the reading of the fixation chart by the patient, crowds on lenses of the indicated power until he has found all movement of the shadow made neutral. When this point is reached, the lenses in the frame are said to indicate in young people the true refractive deficiency of the static refraction; in presbyopic patients, the true refractive deficiency plus the presbyopic demands. If the subjective examination does not show the same findings (and generally it does not), the difference is the measure of the latent error or tonic spasm (and, in presbyopia, the measure of the presbyopia) made manifest in the dynamic examination because of the increased accommodative demands.

This opinion, however, is not universal. Most writers on the subject have held the opinion that dynamic findings represent a refractive status true only for the particular conditions under which the examination is made. Assumedly, then, such findings would represent the active aid needed under such dynamic conditions. Rarely though, except in presbyopia or cases of subnormal accommodation, which condition is analogous to presbyopia, will such a correction be accepted.

Charles Sheard in his recent book, *Dynamic Skiametry*, expresses the opinion that, at most, dynamic skiametry can give us only the negative relative accommodation. Under the heavy accommodative demands of a dynamic skiametric examination made at the usually close distance necessary in this form of examination, the negative relative accommodation is practically the same as the tonic contraction or latent error we are endeavoring to unfold in order to arrive at a definite knowledge of the true static refraction.

It is somewhat of a question in the writer's mind whether relative accommodation really exists. Relative accommodation is described as the difference between the greatest amount of additional accommodation that can be exerted as measured by the dioptric value of added minus spherical lenses, (positive relative accommodation) and the amount of accommodation that can be suppressed as measured by the dioptric value of added plus-spherical lenses (negative relative accommodation) under a *fixed* binocular metre angle of convergence.

We consider convergence remains fixed because diplopia does not occur during such a test: but seldom does diplopia occur in ametropic errors because of positive and negative fusional convergence. There are excellent physiologic reasons for relative convergence, for without it every case of hypermetropia would create a convergent strabismus and every case of myopia a divergent strabismus, but there does not seem to be the same physiologic need for relative accommodation.

According to Savage the innervations controlling the associations of accommodation and convergence are from accommodation to convergence. Granting the truth of this, which is open to some reservations, whenever we accommodate we bring about an associated amount of convergence. By placing a 4Δ base up before one eye and 4Δ base down before the other and using the dot and line of print as described by Sheard in his *Dynamic Ocular Tests* and *Physiologic Optics*, we are able to study this relationship of accommodation and convergence very effectively. By adding minus spheres, thus stimulating greater accommodation, we *always increase* the convergence and by adding plus spheres thus suppressing accommodation we *always decrease* the convergence.

It would seem, therefore, that there is no such condition as relative accommodation in the sense we have always interpreted it, but that the positive range, as we have measured it, merely stimulated accommodation, while negative fusional convergence maintained binocular single vision.

The negative relative accommodation, however, presents a decidedly different condition as there is always present a tonic contraction of the ciliary until the amplitude of accommodation has materially decreased. Under excessive accommodative demands this is assimilated by the plus sphere used in the test.

From an experience of eighteen years the writer is inclined to believe that the Cross interpretation is, in general, true.

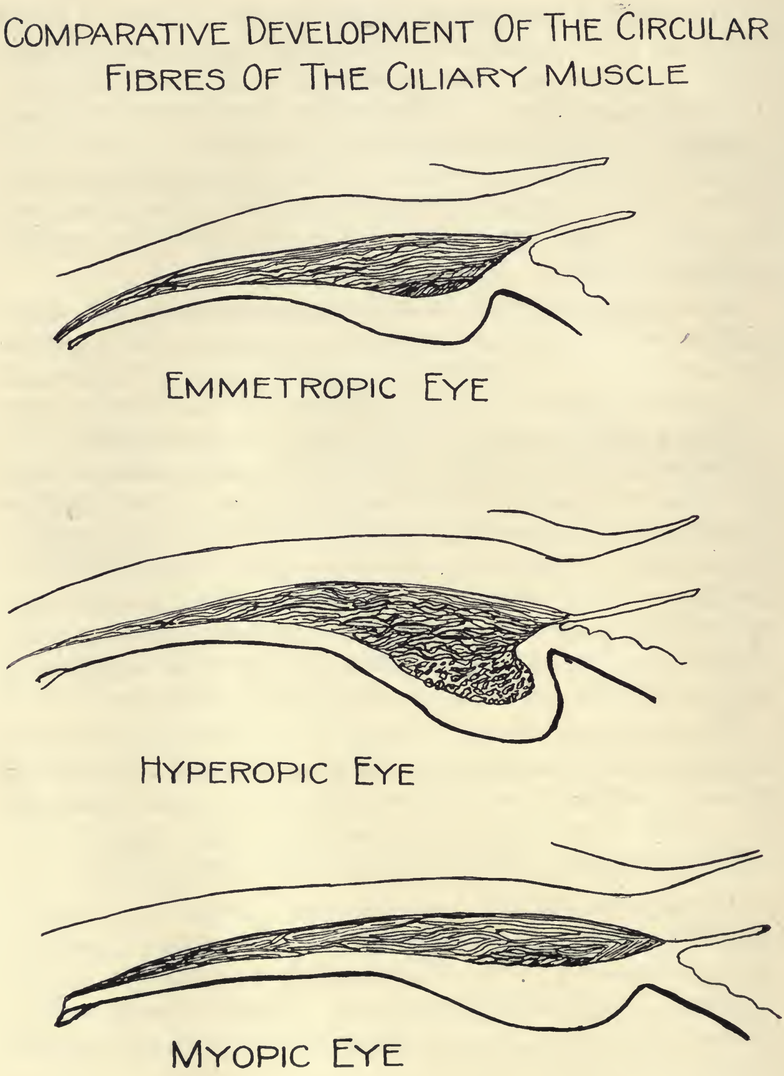
COMPARATIVE DEVELOPMENT OF THE CIRCULAR
FIBRES OF THE CILIARY MUSCLE
EMMETROPIC EYE
HYPEROPIC EYE
MYOPIC EYE

Figure 1. Development of the Circular Fibers of the Ciliary Muscle in Emmetropic, Hyperopic, and Myopic Eyes.

It has been an increasing source of satisfaction on re-examination to find that the dynamic findings remained practically the same during a long period no matter how much the subjective findings and final prescription might vary. In passing it might be said that disagreements between dynamic and subjective findings are always a cause for investigating conditions, (particulary muscular conditions that might interfere with accurate fixation), which might create pseudo refractive findings.

Under the presbyopic age there should normally be a difference of between one and two diopters more hyperopia and as much less myopia. During the presbyopic age the dynamic findings are always increased by at least the amount of the presbyopia for the distance used in examination.

Nearly all text-books on anatomy show the ciliary in emmetropia, myopia and hypermetropia, from which it is obvious that the hyper-developed ciliary of high hypermetropia, through tonicity, will accomplish part of the distance correction even though in accommodation it might not hide the total error. Likewise in myopia the undeveloped ciliary would result in dynamic findings similar to those found in presbyopia, the undeveloped circular fibres not having the potential powers of emmetropia and hypermetropia.

In the early days of dynamic skiametry it was customary to crowd on as much of the supposedly latent correction as possible, in spite of the blurring of distant vision. So commonly did patients thus corrected return after an appreciable period with little or no improvement of distance vision, that many practitioners began to question the dynamic findings as a gauge of the true static refraction. The fact remained, however, that the dynamic findings themselves remained practically the same until the approach of presbyopia began to increase the dynamic findings. Moreover, as presbyopia advanced and an increase in hypermetropia or decrease in myopia was found in the static correction, the difference between dynamic skiametric and subjective findings showed a constant progress toward the amount which represented the presbyopic portion of the findings. Also the increase and decrease in the static refraction gradually approached the approximate amount previously found as a latent error.

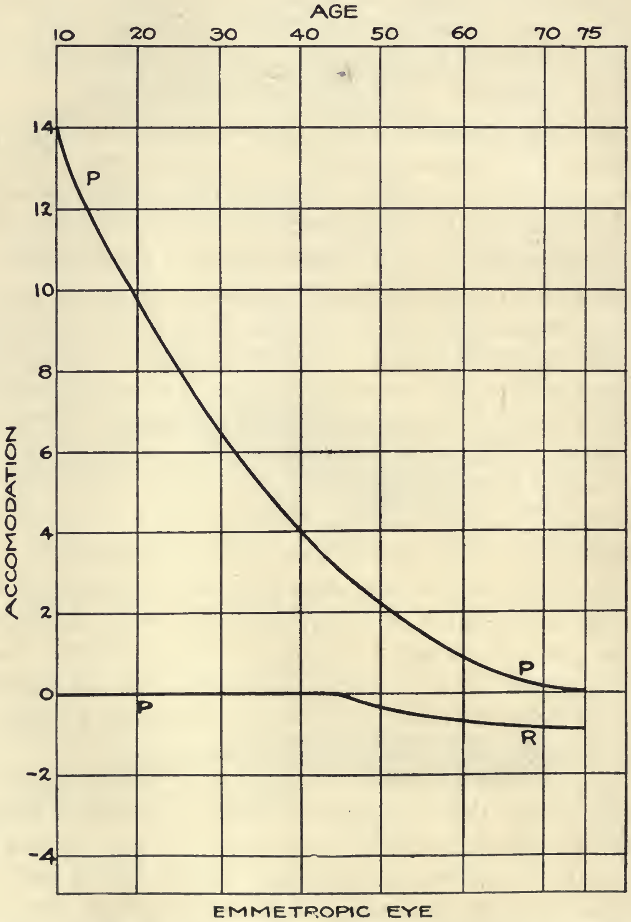

Figure 2. The Punctum Proximum and Punctum Remotum Curves for the Emmetropic Eye.

In a curve P.R. (Punctum Remotum curve) shown in Figure 2 it will be noticed that the line begins to deviate downward at an age point of about 45; indicating that the refraction begins to diminish, *i.e.*, an emmetrope becomes hypermetropic; a hypermetrope, more hypermetropic; and a myope, less myopic. The amount of the diminishing for an emmetrope as indicated by the graph after Donders reaches an average total of about 1.50 D. Coincidently this is about the average difference found between dynamic skiametric and subjective findings. So consistently does the average prove true in practice that the writer usually commences his subjective examination by making an arbitrary deduction of +1.50 D. S. from the findings found dynamically and if there is much variance, he is lead to an investigation of the tonic and dynamic muscular conditions of the eyes for causes that may have made the dynamic skiametric findings faulty.

This graph is generally true for apparently emmetropic cases, cases of low amounts of hypermetropia and nearly all cases of myopia. It is only necessary to start the P. R. line above zero in myopia and below zero in hypermetropia, the amount of the manifest myopia or hypermetropia of early life and plot as illustrated.

A high amount of facultative hypermetropia, however, will show a decidedly greater difference between dynamic skiametric and subjective findings, because of the increased tonic ciliary contraction from hyper-development of the ciliary as shown in Figure 1.

The relatively high amount of latent error found in such cases is not amendable to refractive correction during early life but begins to become manifest earlier than in emmetropia or in low amounts of hypermetropia. Therefore, such cases would present a greater dropping of the P. R. line and usually begin at the early presbyopic age as shown in Figure 3.

Recently, in an attempt to prove the contention above described, the writer was led to an investigation of the difference found between dynamic and subjective findings and

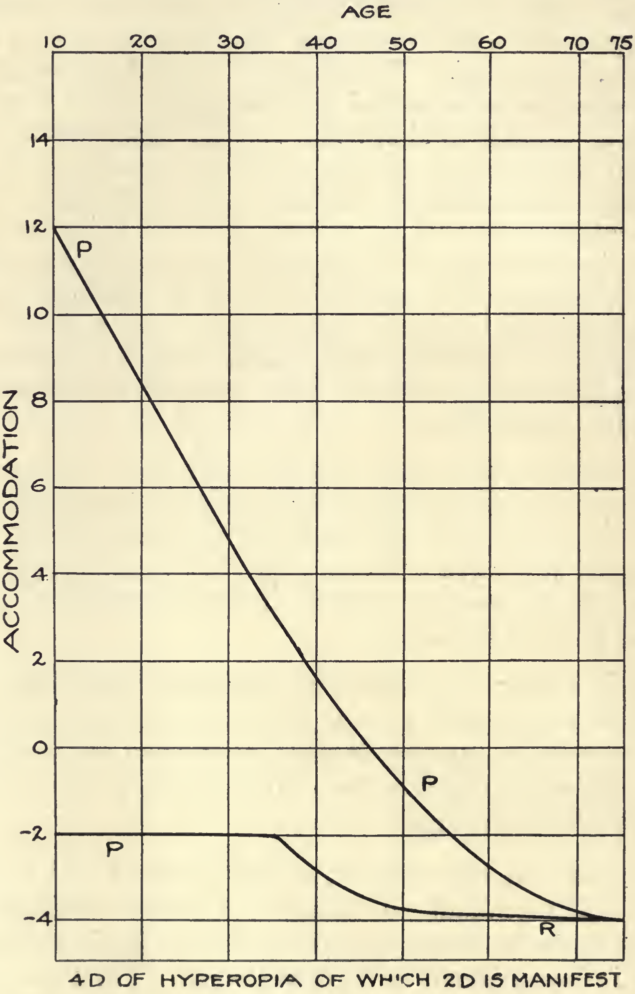

Figure 3. The Punctum Proximum and Punctum Remotum Curves for an Eye having 4 Diopters of Hyperopia, of which 2 Diopters are Manifest.

their comparison with the differences in the amplitude found and amplitude expected. It was hoped to have a comparison of 1,000 cases which constitute a fairly good normal, but to date it has been impossible to compile the record of more than 200 cases. Only cases between 20 years of age and 35 are given. At 20 the eyes are fully developed and beyond 35, the amplitude begins to lessen so rapidly that for the purpose of this paper the above ages were considered better.

If the dynamic findings furnish us the exact refractive status of an eye, the lenses which have been required to make the retina of the examined eye and the nodal point of the examiner conjugate should represent the correction necessary to bring parallel rays of incident light to the retina if the accommodation is nil.

If the subjective findings differ from this dioptric amount due to a tonic contraction of the ciliary, the amplitude should show a proportionately less amount, unless pathologic conditions which would tend toward creating subnormal accommodation were present.

The following examples show how this data was tabulated. Two hundred consecutive cases were taken from the files. Sixty-one had to be omitted because they were highly myopic, or had marked degrees of exophoria, making in all one-hundred and thirty-nine cases for comparison. These cases represent the "run" of daily practice. If conducted for statistical data the comparison could have been made closer by investigating the causes whenever a discrepancy was present. Fifty-seven, approximately 30 per cent, correspond within a quarter to a diopter; thirty-five, approximately 20 per cent, correspond within a quarter to a half diopter and forty-seven, approximately 23 per cent, correspond within from a half to one diopter.

Age	Difference between Dynamic and Subjective Findings		Difference between Amp. found and Amp. expected		
	R.	L.	R.		L.
25	1.25	1.25	−0.50		−0.50
25	1.50	1.50	−1.50		−1.50
38	1.25	1.25	0.00		0.00
25	1.75	1.75	−1.25		−1.25
13	1.25	1.25	−1.50		−1.50
29	1.75	1.75	−0.25		−0.25
26	1.75	1.75	−1.50		−1.50
38	1.75	1.75	0.00		0.00
30	1.50	1.50	−1.00		−1.00
26	2.00	2.00	−2.00		−2.00
16	1.25	1.25	−1.50		−1.50
30	1.00	1.00	−2.00		−1.00
17	1.00	1.00	−2.00		−2.00
32	1.00	1.00	−1.75		−1.75
26	1.50	1.50	−1.50		−1.50
25	1.50	1.50	+1.00		+1.00
12	2.00	2.00	−9.00	Myopic	−9.00
22	1.50	1.50	−2.50		−2.50
23	1.75	1.75	−0.75		−0.75
18	2.00	2.00	−6.00	Myopic	−6.00
20	0.75	1.00	−1.50		−1.00
22	1.00	1.00	−0.50		−0.50
31	1.50	1.50	−0.50		−0.50
31	1.50	1.50	−1.00		−1.00
38	1.50	1.50	−1.50		−1.50

Conclusions

It is therefore the opinion of the writer that:

1. The dynamic skiametric examination, properly made at fixation distances between a quarter and a half of a metre, does give us the *total* refractive error present.

2. The difference between the dynamic and subjective examination represents a tonic contraction of the ciliary, or

presbyopia, which are physiologic conditions. If due to tonic contraction it is not amendable to immediate refractive correction although it gives us valuable advance information as to the prognosis of the static refraction. If due to presbyopia it of course should be given as a reading correction and the amount of the presbyopia deducted to arrive at the static refraction.

3. On the average, the difference between dynamic skiametric and subjective findings should manifest itself as a difference in the amplitude expected and amplitude found.

4. It would also seem to indicate that the condition we call emmetropia is in reality a latent hypermetropia and that myopia of a low degree is in reality emmetropia.

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On Accommodative Exophoria, or the Accommodation Associated with the Act of Convergence

Charles Sheard, Ph. D.

Introduction

AS to the significance and importance of the condition of the lateral muscle balance at the near or reading point and as to what shall constitute a condition of orthophoria at such reading points has received some little attention from various experimenters. Our text-books, encyclopedias, experimental and theoretical papers dealing with the general subjects of phorometry, orthophoria and heterophoria contain but few references to tests upon the muscle balance with the act of convergence, whereas the literature upon the static conditions is voluminous.

Donders (*Accommodation and Refraction of the Eye*, 1864) pointed out the very fundamental relationship between strabismus convergens and hyperopia on the one hand and strabismus divergens and myopia on the other. He discusses (*l. c.* page 110 *et al*) the relation between accommodation and convergence and points out that "the connexion is not absolute and causal" but "that there is a certain degree of independence."

Tscherning (*Physiological Optics*, 2d edition, page 331) says: "Making the examination in this way (Maddox test and ground glass lens) we find in many people a slight degree of latent divergent strabismus for near vision. This condition is often designated as insufficiency of the internal recti. . . . But the internal recti are not weaker than in normal eyes. . . . It is not in the muscles, it is in the innervation of convergence that we must seek for the cause of this deviation."

Stevens (*Motor Apparatus of the Eyes*, page 283) in writing on the topic "Tests at Near Points" says: "In practice, a person with nearly the adjustment of orthophoria will in general show at the near point by such a test (freed from all suggestive lines and marks) a failure of convergence for the distance of the object of about from 4 degrees to 6 degrees of prism. It will be seen that as a test of the *state* of the ocular muscles diplopia of the near-point has no direct value."

In his remarks on the "Test of Muscle Balance with Convergence," Howe (*The Muscles of the Eyes*, Vol. I, page 305) writes: "An examination of the non-asthenopic eyes of the 103 persons . . . showed that perfect muscle balance," (using the von Graefe test of a dot and a vertical ruled line), "at the near point of three meter angles was present in a fraction over 93 per cent. This is a very much larger percentage than that in which we find orthophoria at the far point."

Myles Standish in his section on "Motor Changes in the Ocular Apparatus Associated with Functional Neuroses" (Morris and Oliver, *System of Diseases of the Eye*, Vol. IV, page 783) comments: "An attempt to define the normal muscular balance is somewhat difficult, but in my opinion the normal muscular condition is such that, when looking at infinity, there should be an absolute esophoria of one to two degrees and that upon converging to fifteen inches a normal muscular balance should exhibit an exophoria of about three degrees."

Savage (*Ophthalmic Myology*, 2d edition, page 151) writes: "The test of the lateral muscles and of the obliques should be resorted to in the near also. . . . The dots and the lines should have the same relationship as in the distant test": namely, orthophoria as commonly understood. Further along in his treatise (page 315 *et al*) he discusses intrinsic and pseudo-exophoria and remarks that "when the far test shows orthophoria and the near test shows exophoria the error is pseudo in character" and is dependent upon causes which he names, to wit: myopia or myopic astigmatism and hyper-development of the ciliary muscles.

More recently Theobald (*Transactions of the Section on Ophthalmology*, 1919) in his paper on the "Correction of the Muscular Anomalies of the Eyes" writes: "It is my clear conviction that, unless the ophthalmologist in every case of asthenopia determines the muscle balance, he does not do justice either to his patient or to himself; and this determination of the muscle balance, as I have long since pointed out (*Trans. American Ophth. Society*, 1904), should be made not only for distant vision but for *near vision* as well. . . . .

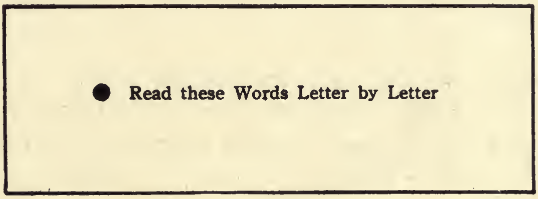
"The fact that, not infrequently, there is marked discordance between the behavior of the muscles at the reading distance and in far vision does not seem to have received the general recognition which it deserves. This discordance one finds not only in the lateral muscles but occasionally in the vertical muscle balance as well. . . . . Of greater practical importance, however, is the fact that unless the muscle balance at the reading point is known, the existence of subnormal accommodative power—the muscle fault which, in my experience, is oftenest overlooked—cannot be recognized. The detection and correction of this anomaly is, in many cases, so helpful that if nothing else were gained by the near muscle-balance tests, this alone would fully repay the time and trouble involved in making them."

And again, Green (*California State Journal of Medicine*, 1912) lays down a few rules, among which we find the following: "In hyperopia with orthophoria for distance and 3 to 4 degrees of exophoria at near, an under-correction of the hyperopia will usually suffice."

From these citations we have good authority for believing almost anything that we desire to accept with reference to the significance and character of the normal muscular balance at the ordinary reading point. It was with the hope of contributing more definite information on this problem that the research, of which the following paragraphs are a report, was undertaken.

Method of Procedure

The subject under test was provided with the static findings and attention directed to the dot and line card (see figure 1) placed in the slide on the bar attached to the phorometer. Two methods of procedure were followed: both, however, in so far as we could discover and for no reason that we know of to the contrary, gave results agreeing the one with the other. The easiest and simplest method consists in swinging up one of the rotary prisms before one eye, for example the right, and inserting 4Δ to 6Δ base up or down in front of this eye. (Or the amount may be divided between the two eyes). Two distinct images of the dot and test line will then be observed. The second rotary prism, swung into position in front of the left eye, may then be operated so as to give prism base in or out until the two dots are in a row. A typical case is illustrated in figure 2. If the prism is inserted base down before the right eye, then the upper image will belong to this eye. If the images are crossed, *i.e.*, if the object as seen by the right eye appears displaced to the left with respect to that seen by the left eye, we should have a condition of exophoria indicated, and the amount of prism, base in, to align the dots would be a measure of the failure of binocular single vision under normal seeing conditions



● **Read these Words Letter by Letter**

Figure 1. Test Object for Use in Accommodative Convergence Tests.

through the medium of convergence as associated with accommodation. A second method is the insertion of the Maddox or other double prism before one eye when, after the other eye is uncovered, three images will be seen, the middle one belonging to the eye wearing no prism. The modus operandi of testing is then similar to that outlined above. An incidental advantage accruing from this last method lies in the ease with which small vertical imbalances may be determined.

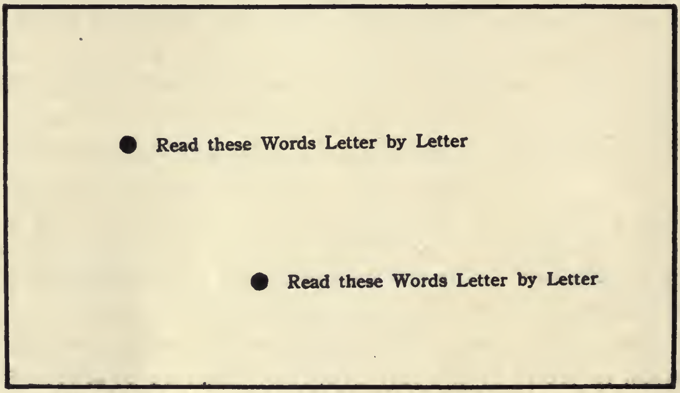

Read these Words Letter by Letter
Read these Words Letter by Letter

Figure 2. Images as Seen under Fusional Dissociation through Vertical Prisms.

The line of type is placed beside the dot in order that the act of accommodation may be enforced and ensured. The patient is instructed to read the words and to report as to the relative positions of the dots. It is, of course, extremely essential that the patient exert the necessary accommodation in order that details be distinguished, otherwise we should be in ignorance as to whether or not such accommodation was in force. Subjects under test invariably report a slight oscillation of the dots, *i.e.*, sometimes a little to the right and then back to the left. The explanation probably lies in the small fluctuations in accommodation, slight tremors due to the systole and diastole and general nervous reactions. In order to ensure accommodation and keep it more constant, therefore, we have generally used a card carrying a line of type printed in brevier face.

All tests discussed in this paper were conducted at a common fixed distance of 12 to 13 inches. This was chosen as a good average distance of most distinct vision, and therefore the clinical data obtained by tests at this point will be of practical value in ocular refraction.

The report which follows covers experimental data on 315 cases exhibiting manifest hyperopic errors ranging from the lowest possible to about three diopters. The data tabulated and plotted in the various curves were obtained from such subjects as met the following requirements: (1) Visual acuity, under the static correction as determined upon, not less that 20/24 to 20/30 as the lowest. (2) No vertical imbalances in excess of ½Δ of hyperphoria or hypophoria. (3) No esophoria or exophoria at 20 feet in excess of 2Δ as a maximum, the subject wearing the static findings which afforded the maximum binocular correction without reducing the visual acuity below the proper standard. (4) No anisometropia greater than 0.50 diopter difference. (5) No pathological conditions. (6) No accommodative spasms or other indications of a pair of eyes in a condition of irritability and hence in such shape as to make fairly consistent results unlikely.

Results

Table I gives the summarized results of the 315 cases reported. Column (1) gives the number of prism dioptries, base in,—hence the measure of the lack of central fusion through the accommodative convergence—required to align the dots; column (2) the number of persons exhibiting the amount specified; column (3) shows a "grouped" arrangement as judged fair and proper by the writer and column (4) gives the percentages of the various groups possessing the amount of exophoria at thirteen inches specified in column (1).

TABLE I

1 Number of Prism Dioptries of Exophoria at 13 Inches	2 Number of Persons	3 Grouped Totals	4 Percentage
0	34	41	13
1	7		
2	29	65	22
3	36		
4	40	81	26
5	41		
6	21	61	22
7	4		
8	36		
9	1	31	11
10	28		
11	2		
12	13	26	8.4
13	2		
14	3		
15	8		
..	..		
18	4	10	3.3
20	6		

Figure 3 gives the curve obtained from the various individual group data when the number of cases is used as ordinate and the various degrees of accommodative exophoria constitute the abscissae. A smooth curve is drawn through the maximum points. This curve will be seen to differ but little in fundamental characteristics from the curve plotted using "grouped totals" in figure 4. In figure 3 the various minima are probably of no significance since the determination of 6Δ of accommodative exophoria, for example, in

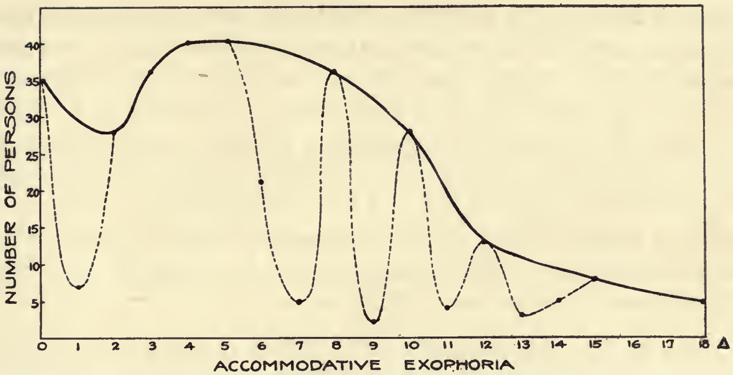


Figure 3. The Relation between Accommodative Exophoria and Number of Persons Tested.

contradistinction to 7Δ thereof in any particular case is doubtless without significance; likewise, these minima will tend to disappear and the points fall upon the smooth curve as the number of cases investigated is increased. However, from the scientific standpoint we feel that the original data should be carefully presented to the reader, who may then in turn critically examine the submitted evidence for himself. All scientific investigators are likely to be open to the criti-

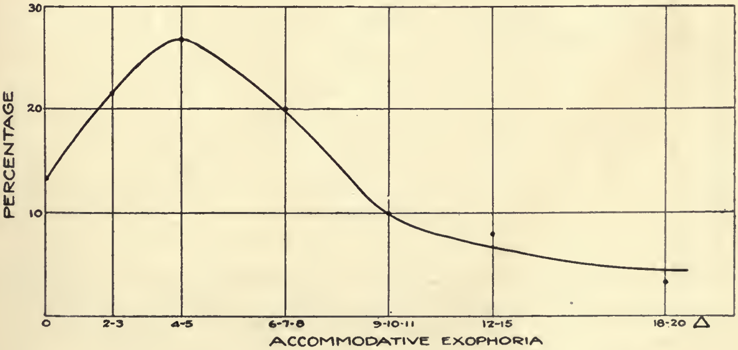


Figure 4. Accommodative Exophoria using Grouped Totals.

cism of forcing the data to confirm in part at least certain pre-conceived ideas or conclusions, whereas other interpretations might be put upon the same. The curve in figure 3 differs from that in figure 4 particularly in the initial portion, for the individual degree grouping process shows almost as large a percentage of persons exhibiting no accommodative exophoria as is indicated for 4Δ to 5Δ of exophoria. However, figure 3 clearly indicates that approximately one-third of all persons examined had an accommodative exophoria at thirteen inches of from 3Δ to 5Δ.

The results diagrammatically shown in figure 4 or tabulated in Table I indicate that nearly 30 per cent of all hyperopes examined exhibited an accommodative (or physiologic) exophoria at thirteen inches of 4Δ to 5Δ. Since the existence of a hyperopic condition is ordinarily assumed to be conducive to ease of convergence, it seems reasonable to conclude that an exophoria, *i.e.*, deficiency of convergence as associated with accommodation, of 4Δ to 5Δ should be assumed to be a normal condition of affairs. We have, at least, the evidence from the data furnished that 70 per cent

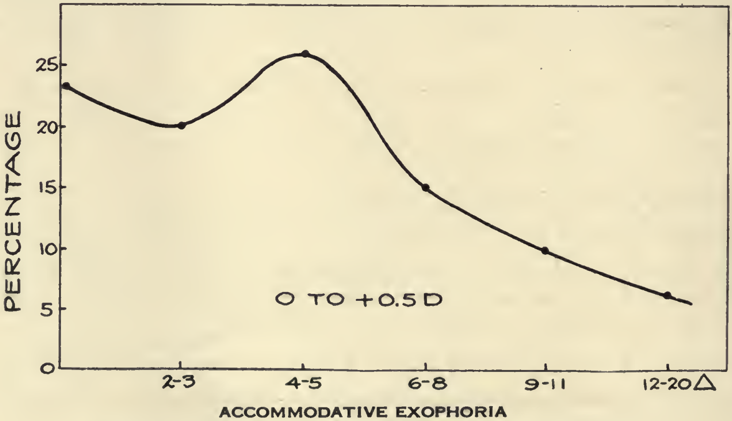


Figure 5. Low Hyperopia and Accommodative Exophoria.

of all the hyperopes examined under the method of selection stated elsewhere showed an accommodative exophoria at the thirteen inch test distance of from 2Δ to 8Δ.

Detailed Investigations on the Relationship between the Amounts of Manifest Hyperopia and Accommodative Exophoria

It is of interest to further analyze the results of this experimentation and to arrange the data in such a way as to show the relationship between the amounts of manifest hyperopic errors (which were corrected before the tests were made) and the lack of central fusion through the medium of convergence as associated with accommodation. The data are tabulated in Table II and graphically diagrammed in figures 5, 6, 7, and 8.

TABLE II

Amount of Accommodative Exophoria (prism diopsters)	Manifest Hyperopia							
	0.0D. to 0.5D.		0.5 D. to 1 D.		1 D. to 2 D.		2 D. to 3 D.	
	No.	Per Cent	No.	Per Cent	No.	Per Cent	No.	Per Cent
0–2	9	22	27	12	3	7.5	4	20
3–4	8	20	46	21	8	20	2	10
5–6	10	25	50	23	15	40	7	35
7–9	6	15	49	22	4	10	3	15
9–11	4	10	20	9.3	3	7.5	2	10
11–on	3	8	22	9.4	6	15	2	10

The curve in figure 7 shows the closest approach to that for the summarized grouped results given in figure 4. Figure 6 is of particular interest since it exhibits the conditions of accommodative exophoria for 214 out of the 315 cases, or practically 70 per cent of all persons examined, hence the

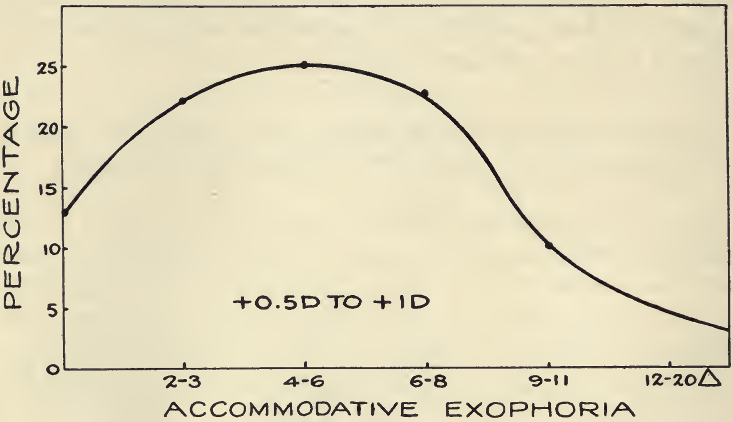


Figure 6. Accommodative Exophoria in Hyperopia.

influence which these data play in the determination of the form of the curve in figure 4. Doubtless hyperopia (including hyperopic astigmatism) of 0.5 to 1 D. is the commonest condition of refractive error: it is, therefore, significant that 70 per cent of all those examined who were in this class exhibited a lack of central convergence accommodatively by amounts varying from 2Δ to 8Δ. The maximum point again

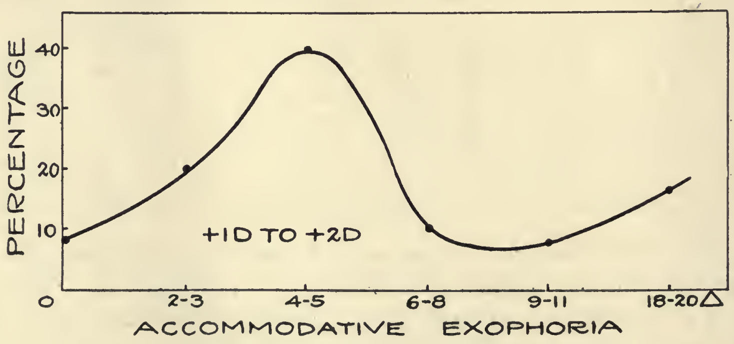


Figure 7. Accommodative Exophoria in Hyperopia.

falls at 4Δ to 5Δ accommodative exophoria. The three curves given in figures 5, 7, and 8, respectively, show a decided maximum at the 4Δ to 5Δ point. It is of interest as well as rather surprising to note that the total percentage of persons exhibiting 4Δ to 5Δ increases with the amount of hyperopia (corrected) present. For we find that hyperopes of 0 to 1 D. show 25 per cent with an accommodative exophoria of 4Δ to 5Δ, while hyperopes of from 1 to 3 D. show an average of 37 per cent having an equal amount of accommodative exophoria.

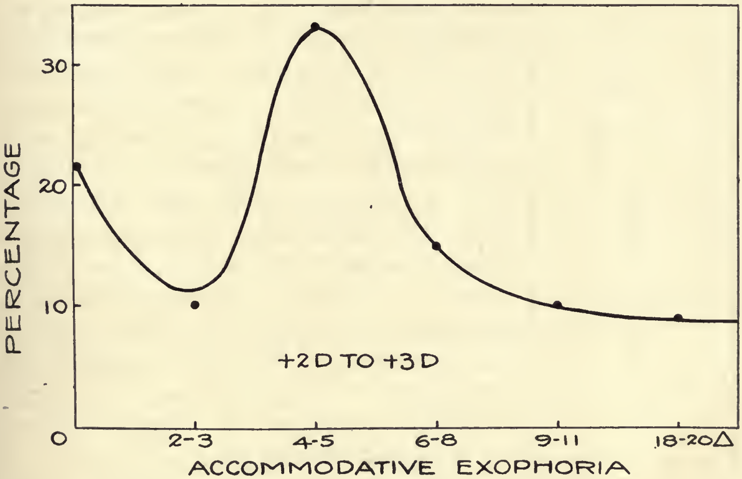


Figure 8. Accommodative Exophoria and Hyperopia.

The results of this paper militate against the doctrine, quite commonly outlined in text books and other treatises on the accommodation and refraction of the eye, that convergence is central; in other words, that the normal and best condition of affairs exists when the total convergence demanded at any fixation point is associated centrally with the act of accommodation. On the contrary, our researches clearly point out that about three-fourths of the convergence needed at the thirteen inch point is that which we have termed accommodative and that the remainder of the convergence necessary for binocular single vision should be supplied through an entirely separate and distinct source of innervation; namely, the fusion centers.

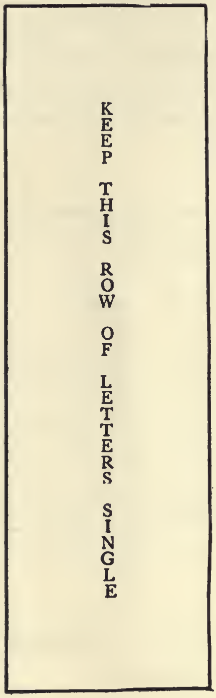


Figure 9. Test-object for Fusion Convergence Reserve Test.

In the practical work of ocular refraction it follows, therefore, that it is of importance to determine the amount convergence associated with accommodation at the normal reading or working distance. The results of this test in any particular case may show an accommodative exophoria ranging from zero to a maximum amount, calculable from the inter-pupillary distance and the distance of the point of fixation, indicating that there is no convergence associated with the act of accommodation. It becomes necessary, then, to determine the positive fusion powers at close points. This may be readily accomplished through the use of a single, vertical straight line or through the use of a vertical row of printed letters as shown in figure 9. The subject, wearing the static findings, if such are called for, holds the card at about thirteen inches or else the card is placed in the sliding carrier of the phorometer. If the row of letters is seen single, then we have evidence that the necessary convergence is produced from some source or other; in general, from two sources; the major portion coming under normal conditions in association with the act of accommodation and the remainder through the fusion convergence. The positive fusion reserve may then be determined as the limit of the amount of prism, base out, which can be placed before the eye (or divided between the two eyes) and still permit of singleness of line. Since we are led to believe from various experiments that not more than one-third to one-half of all of the available fusion convergence can be continuously employed, we have a simple means of investigating some of the intricate problems of the co-ordination of convergence and accommodation.

For the sake of illustration, we shall assume two conditions of affairs which are quite frequently found in practice. Let us assume, in the first case, accommodative convergence tests indicative of 6Δ of exophoria at thirteen inches with a positive fusion reserve of 20Δ. The total fusion available at the point of test (*i.e.*, the usual reading distance) is, therefore, 26Δ of which 6Δ only are constantly demanded. Such a condition of affairs is admirable according to our way of looking at the matter, and does not warrant the reduction of the hyperopic corrections to be given, nor the insertion of prisms for relief, nor again the giving of prism exercises. As a second case, let us take the condition in which the P. D. is 60 mms., thereby demanding 18Δ at 13 inches. If such a pair of eyes should show 16Δ, base in, necessary to align the dots in the accommodative convergence test, there being no tonic errors at distance, we have knowledge that only 2Δ of convergence are associated with the accommodation and that the 16Δ equivalent convergence innervation must be furnished through the channels of the fusion centers to complete the act of binocular single vision. Furthermore, assuming that the positive fusion convergence reserve at 13 inches amounts to 10Δ, we see that the total fusion convergence available at the point of testing is 26Δ, of which 16Δ are constantly demanded for binocular single vision. Hence the burden and drain would be on the fusion centers which are required to supply more than a half of all their available supply. This condition of affairs may lead to ocular fatigue, periods of diplopia at close work, periodic divergent strabismus and so on and would call for a treatment involving such lenticular assistance as might be judged necessary from the data obtained upon the amplitude of accommodation, coupled with relieving prisms, prism exercise or both, and the administration of such therapeutic agents as might be deemed desirable.

TABLE III

Amount of Hyperopic Correction	Number of Persons	Number of Prism Dioptries of Over-convergence at 13 Inches
0.50–1 D.	1	1
0.50–1 D.	4	2
0.50–1 D.	1	4
0.50–1 D.	1	8
1–2 D.	1	1
1–2 D.	1	3
1–2 D.	1	5
1–2 D.	1	7
2 D. and above	2	2
2 D. and above	2	3

In concluding this paper, the writer desires to briefly refer to conditions of esophoria, or accommodative over-convergence, occasionally found at close points. The thousand or more record cards from which the data on the 315 cases reported above were carefully searched for cases in which tonic conditions, wearing the previously determined static findings, did not show an excess of 1Δ exophoria to 2Δ of esophoria, but which did exhibit over-convergence through the accommodative act at close points. A total of fifteen cases was found, of which seven were hyperopes of 0.5 to 1 diopter. The data are given in Table III.

Conclusions

1. Seventy per cent of persons possessing hyperopic errors of from the lowest possible to about three diopters and fulfilling the six criteria relative to muscle balance at distance, absence of pathological and accommodative irregularities, etc., specified in the body of the text, showed 2Δ–7Δ of accommodative exophoria at the thirteen inch test point.

2. This conclusion militates against the view often presented as correct that the act of binocular single vision at close points is normally and ought always to be accomplished wholly through the convergence accompanying the act of accommodation.

3. It seems desirable, therefore, to take as the standard at the ordinary reading distance of about a foot a condition of accommodative exophoria of from 4 to 5 prism dioptries; this deficit being supplied through the fusion centers in the act of binocular single vision at thirteen inches.

Abstracts and Reviews

On a Possible Theory of Vision

Sir Oliver Lodge, F.R.S.

A RESONANCE view of the action of the retina has long been contemplated. The present writer pointed out in *Nature* for March, 1890, that the rods and cones were of reasonably right dimensions to respond, like Hertz resonators, to transverse vibrations falling on their ends with the frequency of luminous waves. (See also *Modern Views of Electricity*, par. 157 A.)

But this gives no indication of how the nerves were thereby stimulated. The subsequent discoveries of excited radioactivity and of the astronomical structure of an atom give a hope of a more detailed theory.

An atom with K, L, M orbits is known to respond to K, L, M frequencies of X radiation and to be ionised thereby. Outlying electrons, such as are often held responsible for chemical or molecular processes, could respond to lower frequencies characteristic of visible light.

And if the orbital radius is estimated which shall enable an electron to respond to red, green or violet light, the order of magnitude is not much larger than the atomic size, *i.e.* 10^{-8} centimetre, even for heavy atoms. The necessary radius varies as the cube root of Moseley's atomic number, and with the two-thirds power of the wave-length.

The suggestion is that the retina may be found to contain atoms in such a condition of incipient instability ("sub-generative" as Professor Eccles calls the state of certain wireless "valves") as to be readily excited by accumulative impulses of the right luminous frequency, and thereby to be stimulated so as to expel an electron and excite a nerve. The energy of expulsion could be only attributable to the incident light on the principle of syntonic accumulation—the ionization energy might be represented as *h n*—and so the extreme sensitiveness of the eye would be accounted for. The atom would be an amplifier or relay, able to respond to the faintest vibration of the right frequency. Retinal fatigue and other phenomena of vision could also be accounted for.

If, however, vision is tri-chromic, the tuning must not be too precise: the responders must be somewhat damped so as to respond over a fair range. In the *Philosophical Magazine* (September, 1919) Professor Barton of Nothingham claims to have shown by mechanical experiments on damped pendulums that three suitably damped and connected vibrators will exhibit phenomena which by an effort may be regarded as analogous to color-vision.

Whether three varieties of vibrator are sufficient, or whether more are necessary, makes no difference to the present communication which is intended to suggest to physico-physiological experimenters the attempt to explain whether chemical substances can be found in a recently removed retina which are able to emit high-speed electrons when subjected to light.

(Abstract written by the Author and appearing in the *British Association*, Section A, Bournemouth, 1919.)

The True Action of Lenses in Ametropia

Lionel Laurance

THIS paper gives a very thorough consideration to the matter of (1) cardinal points of the eye, (2) the equivalent points and foci of a system of two separated lenses and (3) the effects upon the situation of the equivalent plane and the focal plane of the same correction placed at different distances from the eye. The effects of change of position of both convex and concave lenses as well as cylinders are considered.

In near vision, when accommodation is exerted the anterior focus of the eye is shortened and a lens at 15 mm. from the principal plane for distance is most likely beyond it when the eye is accommodated, even after allowing for the changed position of the principal point. If this be so, then the resultant combination of eye and lens becomes weaker if the lens is convex and stronger if concave, than is derived from a given additional dynamic power brought into action.

A generalized formula $F = \frac{F_1 L}{F_2 - L} + d$ enables the calculation of the focal length of a lens which will correct a given case of ametropia when placed at any given distance in front of the first principal plane of the eye. F_1 equals 15 mm. and F_2 equals 20 mm. ordinarily: the distance "d" represents the distance of the correcting lens from the first principal plane. Frequent numerical illustrations form a part of Laurance's article: this adds life to what many readers would otherwise call a "dry" topic.

In concluding his paper Laurance says: "To summarize: the more distant a convex lens is from the eye the greater is its effect, but the weaker is the combination of eye and lens. A higher degree of hyperopia can be corrected, or in near vision artificial accommodation may be obtained by removal of a convex lens outwards and towards the object. The increased action results entirely from the outward removal of E_2—the second principal plane—which more than counteracts the reduction of power or lengthening of F_2."

"The nearer a convex lens is to the eye the less hyperopia does it correct because, although the combined power is increased, E_2 is receded more than F_2 (the posterior focal length) is advanced."

"The more distant a concave lens the less is its effect on the eye, and the *stronger* is the combination of eye and lens. Only a lessened amount of myopia can be corrected and in near vision artificial accommodation can be obtained by the removal of a concave lens outwards and towards the object. The lessened action results from the removal backwards of E_2 not fully counteracting the increase in power or shortening of F_2."

"The nearer a concave is to the eye the more myopia it corrects, since the total combination becomes weaker, and the advancement of E_2 does not counteract the lengthening of F_2."

"Both convex and concave lenses in the anterior focal plane of the eye have no effect on the actual refraction of the latter and therefore none also on the retinal image."

"Further, and this is the essential point of this paper, hyperopia is rarely corrected by a convex lens forming with the eye a more powerful combination, but by leaving it unchanged or by creating a weaker one. On the other hand, myopia is rarely corrected by a concave lens forming with the eye a less powerful combination but by no change or by creating a stronger one. Again, when we give additional convex power for reading we do not at all increase the positive combination but we leave it unaltered if we do not actually weaken it. The effects which we obtain in refraction from the application of lenses are due to changes in the position of the refracting plane and but rarely to changes in refracting power."

"These are, indeed, just the reverse of our ordinary teaching and consideration of the subject, but although of considerable theoretical interest they should not cause us to regard in practice hyperopia and myopia other than as conditions which require respectively augmentation and diminution of ocular refracting power in order that they may be corrected or to regard a presbyope's convex lenses other than as a replacement of the increased converging power which he would have obtained by accommodating, were he able to exert that function."

(Abstracted from *The Institute Journal*, Vol. 8, 1919.)

Some Experiments on the Eye with Different Illuminants

C. E. Ferree, Ph. D. and G. Rand, Ph. D.

THIS research is divided into two parts and appears in the February and November issues of the *Transactions of the Illuminating Engineering Society*, 1919. The first paper deals with a comparison of various Mazda lamps with the kerosene flame for the reason that the belief has been quite commonly held that the kerosene flame gives the best light for the eye and that it should be taken as the model for hygienic lighting.

In carrying out these tests upon ocular fatigue and visual efficiency, a student lamp was used, with opaque shades fixed in every case 2.5 cm. below the center of the luminous source; the lamp was placed in the same relative position in each case; the angle made with the median plane of the observer by a plane passing vertically through the center of the unit was 20 degrees; the reading angle was in every case approximately 40 degrees. The page was illuminated to equal brightness in every case as was proven by measurements with an illuminometer with the test plate removed and calibrated to give readings direcly in candle power per square inch. The distance of the lamp from the page was varied to produce changes in equality of illumination. The angle at which the light fell on the page was the same in all cases.

The test object was illuminated from a separate source. This source was a "mazda, type B," in general, properly hooded and placed to one side of the test object at a dis-

TABLE I

Showing the tendency of the different illuminants used to cause loss of visual efficiency, or power to sustain clear seeing.

Type of illuminant	Dominant Color	Time of day	Total time clear (sec.)	Total time blurred (sec.)	Loss of efficiency expressed in percentage change of ratio
Mazda lamp, type C	Unsaturated yellow, nearly white	9 A. M. 12 M.	144.27 142.67	35.73 37.33	5.34
Mazda lamp, type B, 60 W.	Unsaturated yellow, slightly reddish	9 A. M. 12 M.	139.0 136.7 138.6	41.0 43.3 41.4	6.86
Mazda lamp, type B, 15 W	Unsaturated yellow, slightly reddish	9 A. M. 12 M.	136.2	43.8	7.11
Carbon lamp (metallized filament)	Reddish-yellow	9 A. M. 12 M.	142.5 140.0	37.5 40.0	7.89
Kerosene flame	Orange-yellow	9 A. M. 12 M.	139.17 136.33	40.83 43.67	8.39
Mazda lamp, type C2	Unsaturated blue	9 A. M. 12 M.	138.75 134.12	41.25 45.88	13.14

tance and at an angle needed to give the required illumination. In order to avoid illuminating the surrounding walls and objects, the reflecting screen was perforated with an oblong aperture of such a size as to permit of the use of the most favorable part of the lamp. The test object was made to match the reading page in both brightness and color value. Before beginning each test of a series, the eye was allowed the customary adaptation period. The choice of the length of adaptation period was empirical and was based upon a series of acuity tests.

The reading page illuminated by the light sources had color values ranging from an unsaturated reddish-yellow to a noticeably blue color.

All persons used as observers were familiar with precision measurements in the field of physiologic optics, had no uncorrected eye defects of any consequence and were under thirty years of age. The so-called 3-minute records made after working under various lighting conditions were again followed in this work. Briefly, this method consists in the use of a suitable test object (such as the letters l i or a

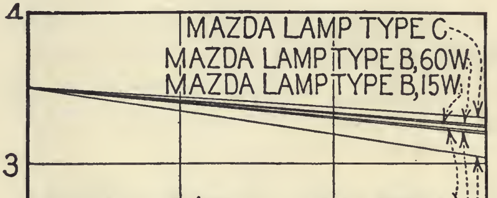


Figure 1. Showing Tendency of Different Lights used to Cause Loss of Visual Efficiency.

TABLE II

Showing the comparison of the tendency of the different illuminants used to cause loss of visual efficiency and to produce ocular discomfort. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Type of illuminant	Per cent loss of efficiency	Time lien of discomfort in seconds (reading)
Mazda lamp, type C	5.34	116.5
Mazda lamp, type B, 60 W	6.86	98.5
Mazda lamp, type B, 15 W	7.11	98.5
Carbon lamp (metallized filament)	7.89	93.0
Kerosene flame	8.39	90.0
Mazda lamp, type C2	13.14	54.5

cross with a dot in the center) so placed that it is readable with some difficulty. The periods of time seen *clear* and seen *blurred* can be recorded on a suitable chronometer and are taken as measures of the fatigue of the accommodation.

Table I shows the tendency of the different illuminants used to cause loss of visual efficiency or power to sustain clear seeing.

Figure 1 is a graphical representation of the results given in Table I.

The total length of the test period is plotted along the abscissa and the ratio of the time the test object is seen clear to the time it is seen blurred is plotted along the ordinate.

The experimentation was concluded by determining for the different illuminants used the relative tendencies to pro-

TABLE III

Showing the tendency of the different illuminants to cause loss of visual efficiency, or power to sustain clear seeing.

Type of illuminant	Dominant Color	Time of day	Total time clear (sec.)	Total time blurred (sec.)	Loss of efficiency expressed in percentage change of ratio
Welsbach mantle, 3% ceria, 97% thoria	Unsaturated yellow	9 A. M. 12 M.	140.0 138.25	40.0 41.75	5.43
Welsbach mantle, 5% ceria, 95% thoria	Reddish yellow more saturated	9 A.M. 12 M.	140.0 137.50	40.0 42.50	7.57
Welsbach mantle, 2% ceria, 98% thoria	Unsaturated yellow with trace of green	9 A. M. 12 M.	144.0 141.50	36.0 38.50	8.29
Kerosene flame	Orange yellow	9 A. M. 12 M.	139.17 136.33	40.83 43.67	8.39
Welsbach mantle, 2% ceria, 98% thoria (shortened)	Unsaturated yellow with trace of green	9 A. M. 12 M.	142.40 139.70	37.60 40.30	8.48
Welsbach mantle, 1% ceria, 99% thoria	Unsaturated yellow with more green	9 A. M. 12 M.	141.0 132.0	39.0 48.0	24.00
Welsbach mantle, 0.70% ceria, 99.3% thoria (shortened)	Unsaturated yellowish-green	9 A. M. 12 M.	139.33 129.33	40.67 50.67	25.51
Welsbach mantle, 0.70% ceria, 99.3% thoria	Unsaturated yellowish-green with more green	9 A. M. 12 M.	139.50 125.50	40.50 54.50	33.14
Welsbach mantle, 0.50% ceria, 99.5% thoria	Greenish (perhaps trace of yellow)	9 A. M. 12 M.	142.0 125.0	38.0 55.0	39.14
Welsbach mantle, 0.25% ceria, 99.75% thoria	Bluish-green, more saturated	9 A. M. 12 M.	142.35 113.50	37.65 66.50	54.86

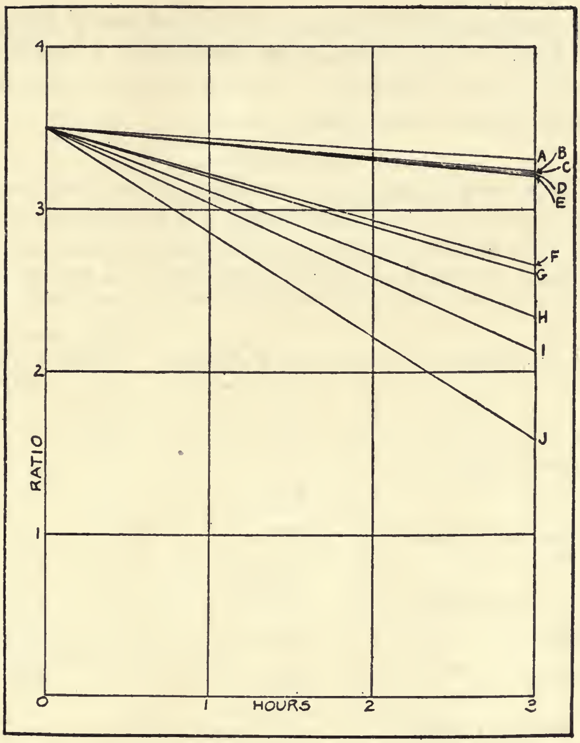


Figure 2. Showing Tendency of the Different Illuminants to cause Loss of Visual Efficiency or Power to Sustain Clear Seeing.

duce ocular discomfort with the eye at work. The results are given in Table II. This shows the comparison of the tendency of different illuminants to cause loss of visual efficiency and to produce ocular discomfort. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

The conclusion is therefore apparently warranted that the common belief among laymen and quite a number of technical eye men "that the kerosene flame as a source of light possesses advantages for the eye not had by other illuminants" is not substantiated.

In a second paper (*Transactions Illuminating Engineering Society*, April, 1919), the author carried out a similar set of experiments with Welsbach mantles having different percentages of thoria and ceria.

TABLE IV

Showing a comparison of the tendency of the different illuminants to cause loss of visual efficiency and to produce ocular discomfort. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Type of Illuminant	Per cent loss of efficiency	Time threshold of discomfort in seconds (reading)
Welsbach mantle, 3% ceria, 97% thoria	5.43	116.0
Welsbach mantle, 5% ceria 95% thoria	7.57	94.0
Welsbach mantle, 2% ceria 98% thoria	8.29	90.0
Kerosene flame	8.39	90.0
Welsbach mantle, 2% ceria 98% thoria (shortened)	8.48	90.0
Welsbach mantle, 1% ceria 99% thoria	24.0	48.0
Welsbach mantle, 0.70% ceria, 99.3% thoria (shortened)	25.51	34.0
Welsbach mantle, 0.70% ceria, 99.3% thoria	33.14	25.0
Welsbach mantle, 0.50% ceria, 99.5% thoria	39.14	21.0
Welsbach mantle, 0.25% ceria, 99.75% thoria	54.86	14.0

Table III shows the tendency of the different illuminants to cause loss of visual efficiency or power to sustain clear seeing.

Figure 2 gives a graphical representation of the results

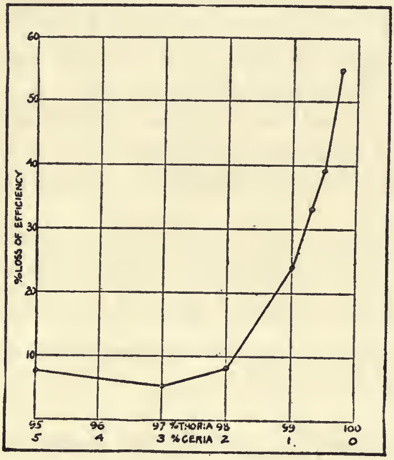


Figure 3. Showing Tendency of the Different Illuminants to cause Loss of Visual Efficiency or Power to Sustain Clear Seeing.

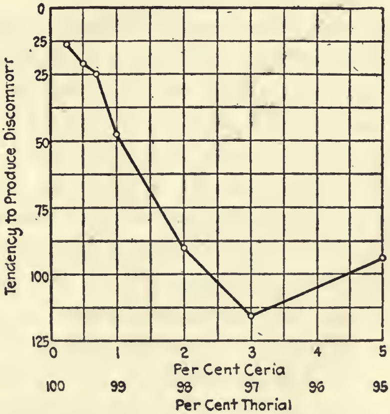


Figure 4. Showing the Tendency of the Different Illuminants to Produce Ocular Discomfort.

given in Table III. In this chart the total length of the test period is plotted along the abscissa and the ratio of the time the test object is seen clear to the time it is seen blurred is plotted along the ordinate.

The relative tendencies to produce ocular discomfort with the eye at work are shown in Table IV. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Figure 3 shows the tendency of the different illuminants to cause loss of efficiency or power to sustain clear seeing. Loss of efficiency in percentage is plotted against composition of mantle.

Figure 4 shows the tendency of the different illuminants to produce ocular discomfort. The tendency to produce ocular discomfort is plotted against composition of mantle.

(Abstracted from the *Transactions of the Illuminating Engineering Society*, Vol. xiii, page 50, and Vol. xiv, page 107.)

The Scattering of Light in the Refractive Media of the Eye

C. V. Raman, M. A.

IN his treatise on *Physiological Optics* (page 180, 1896, German edition), Helmholtz has discussed the explanation of the interesting phenomena observed when a very small and intensely luminous source of light is viewed directly by the eye against a dark background. An enormous number of luminous streamers appear to emerge from the source, and stretch out from it in more or less exactly radial directions. Helmholtz was of opinion that these streamers were due to the diffraction of light at the irregular margin of the pupil of the eye; and this view is supported in his treatise by a description of the phenomena observed when the source of light is seen through a small hole in a metal plate placed in front of the eye so as partially or wholly to screen the margin of the pupil. Some doubt as to the adequacy of the explanation advanced by Helmholtz having been felt by me, a careful study of the effects was undertaken, the results of which are described in the present paper. The phenomena being of a subjective character, the assistance of a number of independent observers with normal vision was obtained in order to confirm my personal observations. This appeared all the more necessary, as the conclusions arrived at as to the origin of the phenomena differ from those of Helmholtz.

The character of the luminous phenomena seen is widely different in the two cases in which the source emits white and monochromatic light, respectively. For observing the phenomena with white light, the most suitable arrangement is to condense the light of an electric arc upon a pinhole in a large dark screen, and to view the issuing light with the eye placed at a distance of about three or four yards from the screen. The luminous pinhole appears surrounded in the first instance by a circular patch full of luminous streaks starting out more or less radially from it, and occasionally crossing each other. These streamers are generally white, but appear here and there tipped with streaks of color. The circular patch is surrounded by a relatively dark ring, outside which again the streamers reappear, passing radially through a luminous colored halo (of angular radius a little less than two degrees of arc) surrounding the dark ring. The halo is, in fact, made up of short sections of the streamers which, here, are strongly colored. Outside the halo, the streamers emerge again, but are much fainter, and they form a broad and somewhat ill-defined ring of luminosity extending to a considerable angular width from the source. The inner margin of this luminous ring is greenish-blue, and the outermost visible periphery is of an orange-red color, but some fainter fluctuations of luminosity and color may be observed within it.

For observation with monochromatic light, a Westinghouse 3000 c. p. silica mercury-vapor lamp with glass dome furnishes a suitable source. The lamp is suspended immediately behind a small aperture in a dark screen and is viewed from a distance of two or three yards. A green-ray filter may be put in front of the aperture, but it is not essential. An alternative arrangement for obtaining a small and powerful source of homogeneous light is to load the carbon rods of an electric arc with plenty of common salt, and to condense the light from the luminous yellow mantle of the arc upon the pinhole in the screen. With either arrangement, the appearance of radial streamers issuing from the source as seen in white light is not obtained. We see, instead, a circular area round the source filled with granular patches of light, and, outside this, a relatively dark ring, followed by a well defined circular halo, and some faint outer rings of luminosity.

A remarkable feature which is worthy of mention is the peculiar circulatory or irregular movement which is best seen in the radical streamers surrounding a white source of light, and less clearly in the granular patches surrounding a monochromatic source of light. These movements disappear gradually, when the eye is held with a fixed gaze towards the source, but start again immediately whenever any movement of the eyeball or of the eyelids occurs.

The effects described above obviously present a striking resemblance to the phenomena observed when light is diffracted by a large number of irregularly placed apertures or particles of uniform size, *e.g.*, lycopodium dust strewn on a glass place. Recently, De Haas has published an elaborate study of such diffraction phenomena, and has shown that the formation of the radial streamers in the coronas surrounding a source of white light, and their replacement by a granular field in monochromatic light, may be explained by considering the interference of light diffracted by individual particles which are assumed to be irregularly distributed over the aperture. The resemblance is not merely qualitative, as some careful visual estimates made by me seem to show that the relative intensity of the streamers in the area immediately surrounding the source and in the first circular halo is about the same as that observed when a source is viewed through a glass plate dusted with lycopodium. There thus seems little doubt that the phenomena described above have to be referred to the diffraction of light by a large number of particles of more or less uniform size included in the structure of the refractive media of the eye. The peculiar movements mentioned above would then naturally be ascribed to the movements of these particles. These may be imitated by observing a source of light through a plate of glass on which a little dilute milk has been flowed. The movements of the diffracted streamers of light can then be easily seen.

Observations show that the angular diameters of the circular patch containing the streamers and of the circular halos surrounding it are entirely independent of the aperture of the pupil of the eye. This is readily proved by altering the intensity of the source of light under observation, with the result that the aperture of the pupil automatically adjusts itself. An ordinary candle-flame at three meters distance, and the light of an electric arc at the same distance or even nearer the eye, give identical measurements for the angular widths, though the aperture of the pupil must have been greatly different in the two cases. This is exactly what we might expect if the effects are due to particles contained in the structure of the eye, but it is very difficult to reconcile with the view of Helmholtz that the phenomena are due to diffraction at the margin of the pupil and, even such an assumption, apart from its being purely hypothetical, fails to explain the observed effects. For, with any change in the aperture of the pupil, the distance between successive corrugations should also alter and influence the observed phenomena. This is inconsistent with the observed independence of the aperture and the observed effects. We are thus led to reject the view that the diffraction at the margin of the pupil determines the phenomena seen.

It is useful in this connection to note that the intensity of the light diffracted by the pupil (supposed perfectly circular) in a direction making 30 degrees of arc with the source would be only 1/3,000,000 of that seen in the direction of the source. (This is calculated from the formula I a $[J_1 (z)/z]^2$ the radius of the pupil being taken to be 2 mm. and $\lambda = 5600$ A. U.) Actually, the streamers surrounding the source can be seen in directions making an angle of 200 degrees and even more with its direction, and it seems safe to say that their intensity half a degree away from the source is a much greater fraction of its apparent intensity than 1/3,000,000.

A further test of the view that the effects are principally due to the structure of the eye and not to diffraction at the margin of the pupil, is furnished by experiments with very thin metal screens containing apertures placed in front of the pupil of the eye. Using a circular hole with smooth edge smaller than the pupil and placed in front of it, the intensity of the streamers surrounding the source of light is reduced, but does not vanish. When the screen is turned about an axis to its plane, the hole being continually kept in front of the pupil, the streamers of light seen in the field remain visible and fixed in position, showing that they are due to the structures of the eye through which the light passes, and not to the margin of the pupil, or the edges of the hole. Another and probably more convincing demonstration is obtained by using a square aperture smaller than the pupil of the eye and placed in front of it. (This may easily be contrived with the aid of four Gillette blades forming the four sides of the very small aperture.) In this case, the effect due to diffraction at the boundaries of the aperture is very clear and marked, but can be shown (on rotating the aperture in its own plane) to be entirely distinct and separate from the phenomena now under discussion.

The angular diameters and intensities of the halos are such as to suggest that we are dealing not with one but with two sets of structures contained in the refractive media of the eye, averaging in size about 13μ and 17μ, respectively. The structures of the latter (smaller) size are indicated by the outermost halo, which appears to be composite in character and due to the superposed effect of the two sets of particles. These structures in the living eye are presumably to be localised in the cornea and in the vitreous humor, as histological evidence of the existence of cellular structures in these bodies is available. Upon this question, however, the author does not venture to express any opinion.

(Quoted from the *Philosophical Magazine*, London. Sixth Series. Vol. xxxviii, p. 568, 1919.)

Diffraction in the Human Eye and the Phenomena of Colored Rings Surrounding Luminous Sources

Charles Sheard, Ph. D.

THIS paper was called forth by virtue of an article by Dr. R. Brudenell Carter on the "Appearance of Color Spectra to the Aged" (*Nature*, November, 1917). Dr. Carter describes the phenomena of colored rings and luminous glow or corona surrounding a sufficiently concentrated bright source. Such a source may be an electric or gas globe in the street or a lighted match held at arm's length in a dark room. Carter concludes that the cause of the color phenomena is the "diminishing refractive power of some of the ocular media," and that the colored rings are merely an "accidental result of unimportant lenticular conditions." With neither of these conclusions is the writer in agreement.

These color rings, so the author says, are not commonly observed because, as a general rule, the light source makes the surroundings too luminous. Or, in other words, there is not sufficient contrast between the light and its environment, such as is obtainable, for example, by striking a match in an otherwise darkened room. And for the further reason that these phenomena are not observed to exist, just as is true in the case of physiologic diplopia, unless the attention of the observer is directed to them. Furthermore, from the explanations which follow, it will be found that the intensity of illumination of the rings is only about two one-hundredths of that of the corresponding intensity of the first maximum (*i.e.*, the original light source), hence, these rings falling upon portions of the retina external to the macula and having low intensity may not be visible in some cases and will not be observed in many others unless first described and then looked for.

The writer has observed these colored rings under favorable conditions for over ten years; and being still under forty years of age, these effects cannot be attributed, in his case at least, to the effects of age *per se* upon the crystalline lens, or other portions of the ocular mechanism. During this period of time his refractive correction has changed from +1.25 D. S. ◯ +0.50 cyl. ax. 90°, to + 4.25 D. S. ◯ +0.50 cyl. ax. 90°.

The attention of many students coming under the instruction of the writer, and of others coming under his observation, has been directed to these phenomena of colored rings; and with but few exceptions they have been readily observed. This has been true irrespective of the refractive condition, whether myopic, hyperopic or astigmatic, and irrespective of whether or not correcting lenses were worn. Hyperopic conditions apparently tend to make the phenomena (with respect to ring No. 1: see later discussion), more readily seen, however. This is believed to be due to the concentration of light, or sharpness of retinal image obtained by virtue of the small pupils, generally accompanying hyperopia; and the nature of the distribution of light upon the retina as affected conjointly by the condition of refraction and chromatic aberration. The size of the pupil, unless extremely and abnormally small, has no effect upon the phenomena. By this is meant that the phenomena are observable alike to those with large or small pupils.

They are also readily observed with ciliary and sphincter muscles relaxed, when viewing sources of light at large distances; or, again, when both are innervated, as in accommodating for such a source at close points. We are in agreement with Carter that these rings are not seen when the light is approached too closely, *i.e.*, within a few inches of the face. The reasons are apparent: First, the contraction of the ring upon the approach of the source, and, secondly, the submerging of the ring in the general central illumination surrounding the source. Also, these rings will not be seen when looking thru a small aperture, such as a narrow stenopaic slit. But the corona and striae radiating out from the light source will be found to be crossed at right angles by a series of parallel colored fringes, which arise from the diffraction effects ob-

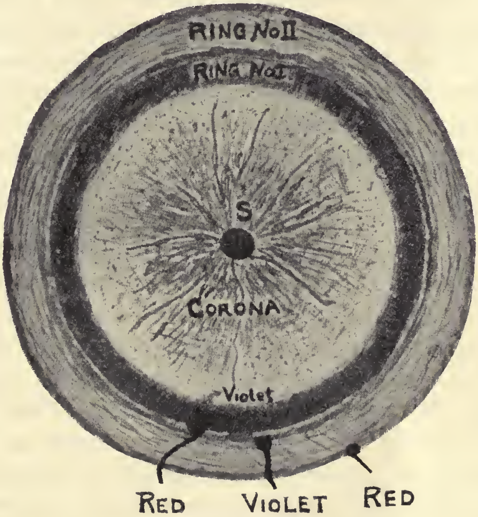


Figure 1. Diagram illustrating Relations of Light Source S, Ciliary Corona, and Rings I and II.

servable thru any narrow slit. In this case the physical phenomena of interference and diffraction of light enter into the effects produced.

One of the most serviceable and convenient sources of light to be used in observing the phenomena under discussion is the small lamp of a self-luminous retinoscope or ophthalmoscope. This light source is steady, small, and brilliant when viewed in a darkened room.

If this, or a similar, luminous source is viewed at any convenient distance, the arrangement of colored rings and ciliary corona, so called, will be somewhat as roughly diagrammed in Figure 1.

The Ciliary Corona.—Surrounding the whole of the luminous source is a general luminous glow, with several prominent striae or rays shooting out in various directions from the central light. This phenomenon is very striking if the light source is brilliant. The name of ciliary corona has been attached thereto. (Tscherning.) This ciliary corona is composed of an infinity of very fine, and ofttimes many colored radiations, which cross thru the whole of the luminous area. Its extent depends upon the intensity of the light source, or the luminous flux entering the observer's eye. Using an arc lamp, or the image of the sun reflected from a convex mirror, there will be found a diameter of the corona which may reach 8 degrees. An examination of these phenomena with monochromatic light causes some minor changes in their character. Under these conditions the corona presents the form of a luminous dust, crossed by few radial striae. Druault says that, under such conditions, there may be seen quite near the luminous area one or two fine black rings, due to diffraction by the border of the pupil. That portion of the luminous "dust" or haze close to the light source appears to have a constant motion of the nature of contractions and dilatations, which probably correspond to changes of the pupil (Druault). However, it is suggested that, if the corona is produced by crystalline lens fibers, these fluctuations may be due to small variations in the action of the accommodative apparatus.

Ring No. I—Surrounding the ciliary corona will be seen the vividly colored ring (marked No. I in Figure 1), presenting the colors from blue to red from the center to the periphery of the ring. If the luminous source is not very bright this ring forms the limit of the corona, but if its intensity is high the diameter of the corona may attain a value double that of the ring. Furthermore, these phenomena appear to be universal. Nearly anyone walking along a street lighted by gas or electric lights may observe them.

Ring No. II—In addition, under conditions to be further discussed, there may be seen a second ring (marked Ring No. II in Figure 1;) somewhat fainter than ring No. I and closely bounding it, with colors arranged in a similar order. The writer has observed both of these rings simultaneously on a few occasions, when the light source was rather powerful and the pupil in a sufficiently dilated condition. The artificial dilatation of the pupil by cocain makes more probable the appearance of this second ring; but in addition it is generally necessary that the light source be brilliant, small, and close at hand. Otherwise the intensity of illumination of the ring by virtue of its size and the position and character of the retinal illumination are too low to make it visible. It is shown that the intensity of this second maximum is only about one-third of that of the first maximum (*i.e.*, the first ring), or about one two-hundredth of that of the original source. We have also to consider the fact that the situation of the retinal image is more peripheral in the case of the second ring, hence making its mental reception and interpretation less likely. The presence of a large pupil would, therefore, be conducive to greater flux of light and hence greater intensity of retinal stimulation.

The author prefers to tabulate the data relative to his own eyes, since he is certain of fair accuracy in this case at least. The determinations of the diameters of the various portions of the colored rings No. I were made by the use of the small ophthalmoscopic lamp, held at distance of distinct vision, and observing (or marking) as nearly as possible the points cut by the various colors as seen upon a celluloid millimeter rule mounted just back of the lamp. No great accuracy in these measurements can be claimed, *i.e.*, within ten per cent probably, and yet the results were very concordant. Knowing, therefore, the diameters of the portions of the colored rings and the distance of observation, the angle (θ), subtended by each of the colors could be found by calculation. The data for Ring No. II were obtained in a similar manner altho with less likelihood of accuracy.

A résumé of the experimental data is as follows:

TABLE I

	Angle (θ)		
Ring	Red	Green-Blue	Violet
	$\lambda = 6500$	$\lambda = 5000$	$\lambda = 4000$
I	3° 40′	2° 40′	2°
II	8°	5° 40′	4° 20′

Ring No. I—Blue green. $\theta = 2° 40'$. $\sin \theta = .0465$. $\lambda = 5000 \times 10^{-8}$ cm. (approximate blue) $= 0.50\mu$. $m/\pi = 1.333$. Hence from $R = m\lambda/\pi \sin \theta$, we find that $R = 0.0009$ cm. or $R = 9\mu$.

Ring II—Blue-green $\theta = 5° 40'$. $\sin \theta = .098$. $\lambda = 5000 \times 10^{-8}$ cm. (approximate blue) $= 0.5\mu$. $m/\pi = 1.333$. Hence substituting in $R = m\lambda/\pi \sin \theta$ we have $R = 0.00066$ cm. or $R = 6.6\mu$.

It is to be remarked at this point that the sets of readings and hence calculations upon Ring No. I are much more likely correct than in the case of Ring II, in which difficulties of low intensity (S) make the determination of the angles (θ) less certain.

If, therefore, we accept the experimental data and results as being reasonably accurate and the applications of the theory of diffraction by circular apertures or discs as being permissible in the case under discussion, we arrive at the conclusion from the calculations tabulated above that Ring II is not a second effect of which Ring I is the first effect, but that is due to a set of particles or apertures of much smaller diameter as shown in set C, Table II. We conclude, therefore, that the apertures or particles giving rise to Ring I

TABLE II

Set	Θ	$\lambda \times 10^{-8}$ cm.	m/π	$R = \frac{m\lambda}{\pi \sin \theta}$	D = diameter of particle	Ring
A	2°	4000	.82	10μ	20μ	I
A	2° 40′	5000	.82	9	18	I
A	3° 40′	6500	.82	8.5	17	I
				Av.= 9.2μ	Av.=18.4μ	
B	4° 20′	4000	1.33	6.8μ	13.6μ	II
B	5° 40′	5000	1.33	6.7	13.4	II
B	8°	6500	1.33	6.4	12.8	II
				Av.= 6.6μ	Av.= 13.2μ	
C	4° 20′	4000	.82	4.4μ	8.8μ	II
C	5° 40′	5000	.82	4.1	8.2	II
C	8°	6500	.82	3.9	7.8	II
				Av.= 4.2μ	Av.= 8.3μ	

have an average diameter of 0.00184 cm. or 18.4μ and, in turn, those producing Ring II an average diameter of 8.3μ, unless this ring is due to second order diffraction effects of the same corpuscles, when calculation gives the average diameter of the particles as 0.00132 or 13.2μ.

Ring No. I—We turn, therefore, to anatomic investigations to see if there is evidence of cells or fibres having diameters of the approximate amounts specified above. Schiötz measured the dimensions of the *superficial cells* of the *epithelium* of the *cornea* and found sizes varying from 25μ to 40μ. He futhermore found that on exposing the cornea to the action of distilled water for some time he observed a beautiful system of rings of which the first corresponded practically to the Ring I. He remarks that it is a little smaller, however, which is readily accounted for by the action of water upon the cells and apertures. These results of Schiötz are in close experimental agreement with the values of the diameters of the particles obtained by Druault in 1899. This latter writer found a value of $\theta = 2° \ 12'$ for sodium light of 5,900 t. m., which gives a value of D (diameter of the particles as an average), equal to 0.0025 cm. or 25μ. And again, Druault found, on looking through a dead cornea, a ring the dimensions of which differed but little from those of Ring I and which he claims was undoubtedly due to the *endothelium* of *Descemet's membrane*, for he could remove the entire epithelium of the anterior corneal surface without producing any effect, but the ring disappeared as soon as the endothelial layer was touched.

Ring No. II—The Ring No. II Druault attributes to the crystalline fibers which are arranged in the form of a network or grating. The size of the openings or slits between these fibers can be calculated from the formula for a series of parallel rulings (*i.e.*, plane grating), which states that $m\lambda = d \sin \theta$, where d is the slit width. If such is done, using Druault's data, we find that

$$d = \frac{m\,\lambda}{\sin\,\theta} = \frac{0.59}{\sin\,31° \ 33'} = 9.5\mu$$

Anatomists (see Norris and Oliver), tell us that the superficial lens fibres measure from 0.0010 cm. to 0.0012 cm. or 10μ to 12μ. Hence, if these lens fibers were, in the main, parallel each to each, giving a series of parallel slits, it would be justifiable to apply the formula given above for diffraction by parallel slits. However, we know that the lens fibers are parallel only in so far as the major portion of those forming any one sector of the "lens-star" may be considered parallel. Likewise, if these fibers were in the main parallel we should obtain the phenomenon of diffraction by parallel slits, which shows a linear spectrum and not a circular one as in the case of apertures or discs. Such a linear spectrum is not experimentally found. Hence the use of the above formula for parallel slits does not seem to be in order.

The ciliary corona, with its luminous dust and striae, is without doubt due to the lens fibers in part and again in part to the lens star. These fibers and lens star are known to exist subjectively as the result of unequal refraction of light by the various sectors into which the crystalline lens is roughly divided. The pronounced criss-crossing of sectors of lens fibers in different layers, and the fine mesh appearance developed, serve admirably to account for the appearance or character of the luminosity immediately surrounding the light source.

Glaucomatous patients may see rings which resemble those described in the preceding paragraphs. In cases of glaucoma, however, these rings are larger and assume an angular diameter of 10° to 12°. Since the size of the ring increases as the distance between corpuscles or cells producing them decreases, Schiötz attributes the origin of the glaucomatous rings to the deepest layer of the corneal epithelium. Experiments on pigs' corneae, so arranged that salt water could be forced into them, showed that a large circle of diffraction was produced when the liquid penetrated into the deeper epithelial layers.

The principal conclusions are:

(1) The universality of colored rings and coronae surrounding luminous sources under fairly favorable conditions of observation.

(2) These rings are due to the diffraction of light by the constituent parts of one (or more) of the ocular media.

(3) The results of experimentation, based on the theory of diffraction of circular particles or discs, when compared with anatomic data indicate that the *first* (which is commonly the only one seen) ring is due to diffraction bythe cells of the anterior epithelial layer of the cornea or possibly to the endothelium of Descemet's membrane (Druault).

(4) The *second* ring is evidently due to diffraction by particles of a smaller size than those which produce the first ring. The writer suggests the inner layers of the anterior epithelial portion of the cornea. This ring has been attributed by Druault to the lens fibers, but reasons are advanced indicating that such a view is not probable.

(5) The *ciliary corona* is without doubt due to the lens fibers and the *striae* to the lens star.

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Refraction and Visual Acuity of the Human Eye

James P. C. Southall, A. M.

1. Positions of the Cardinal Points

FROM the purely optical standpoint the human eye is to be regarded as a refracting system composed of the cornea and the crystalline lens which is at any rate approximately symmetrical around a straight line which is called the optical axis of the eye and which for practical purposes may be defined as that normal to the anterior surface of the cornea which passes through the centre of the pupil. A real inverted image of an external object on which the eye is focused is formed on the retina just as a photographic lens casts an image on the ground glass screen of a camera or on the sensitized plate or film which is inserted in the camera in place of the focusing screen; but here the resemblance between the eye and a camera ceases, a fact which is generally not sufficiently emphasized. The most sensitive part of the retina on which the image is sharply in focus is comprised within a very small area, whereas the photographic plate must be equally sensitive all over; but it is the marvellous mobility and adaptability of the eye which is its chief claim to distinction as compared with any artificial system of lenses. A camera is focused by moving the photographic lens as a whole towards the object or away from it; but the eye is focused by changing its refracting power which is divided into two parts, a principal part which is constant and much larger than the other and which is due almost entirely to the first surface of the cornea, and a smaller variable part which is contributed by the crystalline lens and which acts in some sense like a fine adjustment. This crystalline lens, contained in a capsule, is composed of a beautifully transparent substance which seems to be arranged in layers of progressively increasing index of refraction around a somewhat harder interior core. In addition to its other remarkable properties this substance possesses a certain peculiar elasticity whereby within certain limits the form of the lens can be altered by almost insensible muscular effort, in such fashion that when the force ceases to be exerted, the lens returns of its own accord to its original shape and power. This deformation is almost entirely confined to an increase of curvature of the anterior surface of the lens. The focusing process in the eye is called accommodation, and, as is well known, the power of accommodation diminishes gradually but steadily with advancing years until finally in senility it vanishes altogether.

Thus, although the positions of certain points on the optical axis of the eye may be regarded as stationary and permanent, the so-called cardinal points of the optical system (focal points, principal points, nodal points, etc.), are variable depending on the state of accommodation, and yet, to be sure, some of these latter may be more nearly stationary

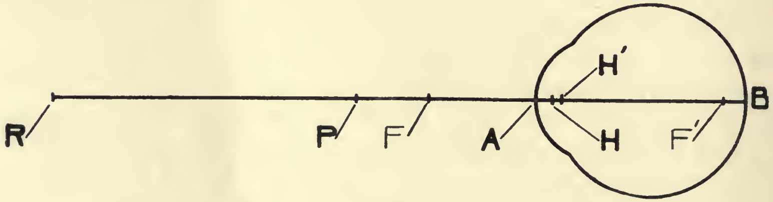

FIG. 1

than others. As far as possible the fixed points of the eye will be designated in the diagrams by heavy black capital

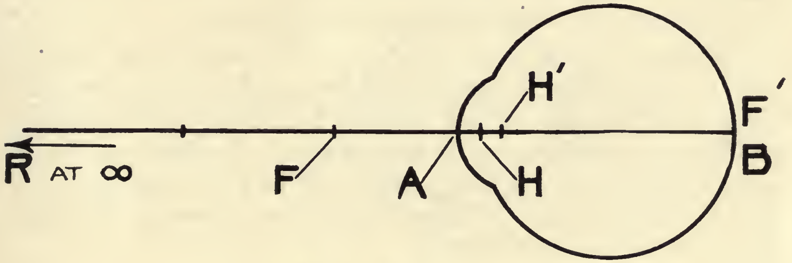

FIG. 2

EMMETROPIC EYE, ACCOMMODATION RELAXED

letters, whereas those points whose positions alter during accommodation will be indicated by ordinary capital letters. Two fixed points which may be mentioned first are the point (**A**) where the optical axis crosses the anterior surface of the cornea and the point (**B**) where it meets the retina (Fig. 1). The axial length of the eyeball (**AB**) remains constant in the case of a given individual, although some eyes may be abnormally long or short (axial ametropia).

The first focal point of the eye (F) lies on the optical axis in the air in front of the eye. When accommodation is entirely relaxed, this point recedes to its farthest position from the eye, and in this position it will be designated by **F**; and on the other hand when the eye is exerting its maximum accommodation the first focal point is nearest the eye, which position will be designated by $\mathbf{F}_{\max}$. The length of the eyeball of Gullstrand's schematic eye (which represents the eye of an adolescent) is $\mathbf{AB} = 24$ mm.; and the distances of the points **F** and $\mathbf{F}_{\max}$ from the vertex of the anterior surface of the cornea are:

$$\mathbf{AF} = -15.707 \text{ mm.,} \quad \mathbf{AF}_{\max} = -12.397 \text{ mm.}$$

(Throughout this paper the positive direction along the optical axis is the direction along this line which light pursues on entering the eye, so that all distances measured away from the eye are to be reckoned as negative.)

The second focal point of the eye (F′) lies on the optical axis in the vitreous humour, either at **B** or not very far from it on one side or the other. According as the accommodation is a minimum or a maximum, the position of the second focal point will be denoted by **F′** or **F′**$_{\text{max}}$, respectively; and in Gullstrand's schematic eye the distances of these points from the cornea are:

$$\mathbf{AF'} = +24.387 \text{ mm.}, \quad \mathbf{AF'}_{\text{max}} = +21.016 \text{ mm.}$$

When the second focal point (**F′**) of the passive eye falls on the retina at **B**, the eye is said to be emmetropic (Fig. 2); otherwise, it is said to be ametropic. Moreover, an ametropic eye is described as myopic (Fig. 3) or hypermetropic (Fig. 4) according as the second focal point (**F′**) is or is not nearer the cornea than the retinal point **B**. Thus, for example, Gullstrand's schematic eye is not emmetropic but slightly hypermetropic inasmuch as the second focal point (**F′**) is not on the retina but 0.387 mm. beyond it, according to the data given above.

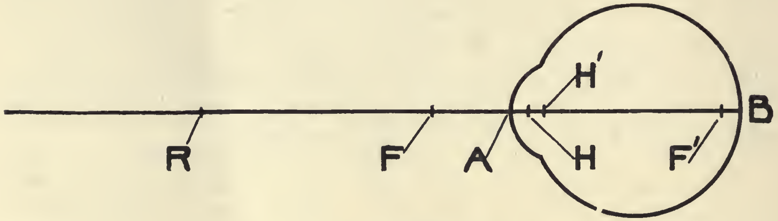

FIG. 3

MYOPIC EYE ACCOMMODATION RELAXED

When the eye is entirely passive, the object-point (**R**) on the optical axis which is conjugate to the retinal point (**B**) is called the far-point of the eye (*punctum remotum*); and,

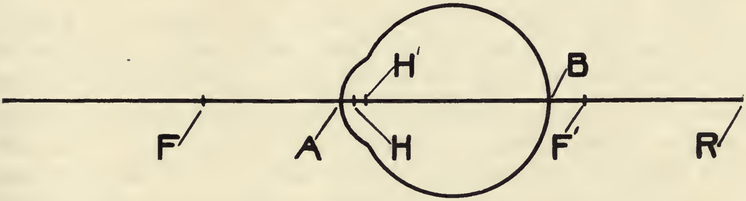

FIG. 4

HYPERMETROPIC EYE, ACCOMMODATION RELAXED

similarly, when accommodation is exerted to the utmost, the object-point (**P**) on the optical axis which is conjugate to the retinal point (**B**) is called the near-point of the eye (*punctum proximum*). The distance from **R** to **P** is called the range of accommodation, and the unaided eye can see distinctly only such object-points on the axis as lie within this range. The far point of an emmetrope is the infinitely distant point of the optical axis, whereas the far point of an ametrope is at a finite distance from the eye, being situated

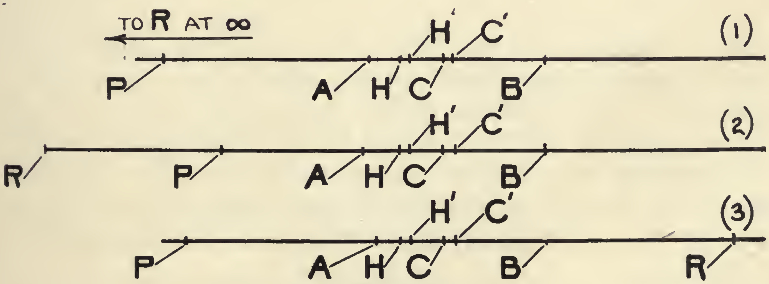

FIG. 5

FAR POINT (R) AND NEAR POINT (P)

(1) EMMETROPIC EYE, (2) MYOPIC EYE, (3) HYPERMETROPIC EYE.

in front of a myopic eye (**AR** < 0) and behind a hypermetropic eye (**AR** > 0), so that in the latter case it is not a "real" object-point at all but "virtual" (see Fig. 5).

The principal points of the eye are the pair of conjugate points on the axis for which object and image are equal in every respect, that is, for which the magnification-ratio is equal to $+1$ (and consequently they are sometimes called also the "unit points" of the optical system). They lie close together between the cornea system and the lens and not very far from either. Owing to the circumstance that the principal points of the eye are indeed quite near the anterior surface of the crystalline lens, their positions remain very nearly stationary during the entire process of accommodation, which, as has been remarked, is mainly effected by a change of curvature of the anterior surface of the lens. For example, in Gullstrand's schematic eye, if the positions of the principal points are designated by **H**, **H′**, their precise locations are as follows:

Accommodation relaxed: $\mathbf{AH} = +1.348$ mm.,
$\mathbf{AH}' = +1.602$ mm.;

Accommodation maximum: $\mathbf{AH}_{\max} = +1.772$ mm.,
$\mathbf{AH}'_{\max} = +2.086$ mm.

Thus it appears that the total displacement of each of these points during accommodation amounts to less than half a millimetre, which may be disregarded entirely since it is extremely difficult, if not impossible, to make measurements in the living eye which are accurate within half a millimetre. By virtue of this stability the principal points of the eye are therefore particularly suitable as points of reference.

The earlier writers on physiological optics attached great importance to the nodal points of the eye, but nowadays these points have lost much of their significance, and we need not pause to consider them here.

2. The Refracting Power of the Eye (F).

The focal lengths of the eye (f, f') are the distances of the principal points measured from the focal points; thus, the first focal length is $f = \mathbf{FH}$ (which is therefore positive in sign, being measured in the direction of the incident light), and the second focal length is $f' = \mathrm{F'}\mathbf{H}'$ (which is negative in sign, being measured in the direction opposite to that of the first focal length). The focal lengths of the eye are not only opposite in sign, but their absolute values are different, because the last medium of the system, the vitreous humour whose index of refraction is $n' = 1.336$ is different from the first medium which is usually air of index $n = 1$; and the two focal lengths of an optical system are always connected by the relation: $f' : f = -n' : n$.

The refracting power of the eye, denoted by F, may be defined as the product of the reciprocal of the first focal length by the index of refraction of the first medium; that is,

$$F = \frac{n}{f} = -\frac{n'}{f'}; \qquad (1)$$

where if the distances f, f' are measured in metres, the refracting power F will be given in dioptries; or if the unit of length is a millimetre, the refracting power will be in Kilodioptries (1 Kdptr = 1000 dptr).

Since with increasing accommodation the focal points F, F′ move in opposite directions towards each other, the focal lengths themselves diminish and the refracting power increases. The focal lengths are longest and the refracting power is least when accommodation is relaxed entirely, in which case we shall use the following symbols:

$$\boldsymbol{f} = \mathbf{FH}, \boldsymbol{f}' = \mathbf{F'H'}, \boldsymbol{F} = \frac{1}{\boldsymbol{f}}, (n = 1);$$

whereas in case of maximum accommodation:

$$f_{\max} = \mathbf{F}_{\max}\mathbf{H},\ f'_{\max} = \mathbf{F}'_{\max}\mathbf{H}',\ F_{\max} = \frac{1}{f_{\max}}.$$

Thus, with the numerical data given above for Gullstrand's schematic eye we shall find the following values of these magnitudes:

Accommodation relaxed: $f = +17.055$ mm.,
$f' = -22.785$ mm., $F = +58.64$ dptr.
Accommodation maximum: $f_{\max} = +14.169$ mm.,
$f'_{\max} = -18.930$ mm., $F_{\max} = +70.57$ dptr.

3. The Refraction of the Eye

Suppose the eye is accommodated to see distinctly an axial object-point at M whose distance from a certain other point O on the axis of the eye may be denoted by $z = \mathrm{OM}$, so that z may be called the abscissa of M with respect to the point O as origin. The reciprocal of this abscissa multiplied by the index of refraction of the first medium (n) is called the *refraction of the eye* with respect to the point O for the given state of accommodation and is denoted by Z; thus $Z = n/z$.

The abscissa of M with respect to the first principal point of the eye is denoted by $u = \mathbf{H}\mathrm{M}$; and the principal-point refraction of the eye is denoted by $U = n/u$.

Moreover, the abscissa of M with respect to the first focal point of the eye is denoted by $x = \mathrm{FM}$; and the focal-point refraction of the eye is denoted by $X = n/x$.

Since

$$\mathrm{FM} = \mathrm{F}\mathbf{H} + \mathbf{H}\mathrm{M}, \quad \text{or} \quad x = f + u,$$

the focal-point refraction and the principal-point refraction are connected with each other by the following relation:

$$X = \frac{F \cdot U}{U + F}, \quad \text{or} \quad U = \frac{F \cdot X}{F - X} \quad . \qquad (2)$$

If accommodation is entirely relaxed, the object-point M coincides with the far point of the eye (**R**). The distance of the far point from the first principal point is sometimes called the far-point distance, and it is denoted by $\boldsymbol{a} = \mathbf{HR}$. The reciprocal of this distance (multiplied by the index of refraction of the medium in front of the eye) is the measure of the so-called *static refraction* of the eye with respect to the first principal point, which will be denoted by $A = n/\boldsymbol{a}$. For an emmetropic eye the static refraction $A = 0$; whereas for an ametropic eye the static refraction is different from zero, being negative for a myopic eye ($A < 0$) and positive for a hypermetropic eye ($A > 0$).

The static refraction may be measured also from the first focal point (**F**); and if we put $\boldsymbol{x} = \mathbf{FR}$, $X = n/\boldsymbol{x}$, the connection between the two expressions for the static refraction is given as follows:

$$X = \frac{F \cdot A}{A + F}, \quad \text{or} \quad A = \frac{F \cdot X}{F - X}.$$

If, finally, the accommodation is a maximum, the object-point M on which the eye is focused will lie at the near point, and if the near-point distance is denoted by $\boldsymbol{b} = \mathbf{HP}$, then we have for the so-called *dynamic refraction* of the eye $B = n/\boldsymbol{b}$.

If the distances denoted above by small italic letters are expressed in terms of the metre as unit of length, the corresponding magnitudes denoted by capital italic letters will be given in dioptries.

The amplitude of accommodation is equal to $(A - B)$.

4. The Image Equations

When an object of height p is placed at right angles to the optical axis at a point O, an image of height p' will be formed in the transversal plane at the point O′ conjugate to O; and the ratio $m = p'/p$ is the so-called magnification-ratio with respect to the pair of conjugate points O, O′. Theoretically, this ratio between the size of the image and the size of the object may have any value whatever, positive or negative, depending merely on the selected position of the object-point O. Thus, for example, for the pair of principal points $\mathrm{m}=+1$; for an object lying in the first focal plane of the optical system the value of m is infinite; and for an image formed in the second focal plane $\mathrm{m}=0$. According as the image is erect or inverted, the sign of m will be positive or negative, respectively.

Let us take the pair of conjugate points O, O′ as reference points for object-space and image-space, and let M, M′ designate the positions of another pair of conjugate axial points, whose abscissæ with respect to O, O′ may be denoted by z, z', that is, $z=\mathrm{OM}$, $z'=\mathrm{O'M'}$. Moreover, let n, n' denote the indices of refraction of the first and last media of the optical system; then z/n, z'/n' are the so-called "reduced abscissæ" and their reciprocals $Z=n/z$, $Z'=n'/z'$ are called the "reduced vergences" with respect to O, O′.

Now if an object of height y is placed at M, which is reproduced at M′ by an image of height y', the *image-equations* referred to the points O, O′ may be written as follows:

$$\mathrm{m}^2\cdot Z'=Z+\mathrm{m}\cdot F, \qquad \mathrm{m}\cdot y'\cdot Z'=y\cdot Z. \tag{3}$$

Thus, for example, in case the reference points O, O′ are identical with the principal points of the eye (**H**, **H**′), then $\mathrm{m}=+1$; and for this special pair of points we shall write u, u' and U, U' in place of z, z' and Z, Z', respectively, that is, $u=\mathbf{H}\mathrm{M}$, $u'=\mathbf{H}'\mathrm{M}'$, $U=n/u$, $U'=n'/u'$, and consequently the image-equations referred to the principal points will be written as follows:

$$U'=U+F, \qquad y'\cdot U'=y\cdot U. \tag{4}$$

When the image is sharply focused on the retina, the point M′ coincides with the retinal point **B**, that is, this latter point is always conjugate to the axial object-point for which the eye is accommodated; and hence $u'=\mathbf{H}'\mathbf{B}=\boldsymbol{a}'$, where $\boldsymbol{a}'$ being in fact a measure of the length of the eye-ball remains constant during accommodation. Accordingly, in the preceding equations we may put $\boldsymbol{A}'=n'/\boldsymbol{a}'=U'$, so that for the optical system of the eye the image-equations referred to the principal points may be written as follows:

$$\boldsymbol{A}' = U + F, \qquad y' \cdot \boldsymbol{A}' = y \cdot U. \tag{4a}$$

Moreover, when accommodation is relaxed entirely, then we must put $U = \boldsymbol{A}$, and consequently in this special case:

$$\boldsymbol{A}' = \boldsymbol{A} + \boldsymbol{F}, \quad y' \cdot \boldsymbol{A}' = y \cdot \boldsymbol{A}, \text{ (accom. relaxed).} \tag{4b}$$

Thus, in general when an eye whose static refraction is $\boldsymbol{A}$, is accommodated to see distinctly an object of height y lying within its range of accommodation, the following relations hold:

$$\boldsymbol{A} - U = F - \boldsymbol{F}, \qquad \frac{y'}{y} = \frac{U}{\boldsymbol{A} + \boldsymbol{F}} \,. \tag{5}$$

For example, from the first of these formulæ we can determine the value of the refracting power (F) corresponding to a given refraction (U); thus, in the case of an axially myopic eye of -5 dptr., for which therefore $\boldsymbol{F} = 58.64$ dptr. and $\boldsymbol{A} = -5$ dptr., we find: $F = \boldsymbol{A} + \boldsymbol{F} - U = (53.64 - U)$ dptr.; and if the eye is accommodated for an object 12.5 cm. from the first principal point, that is, if $U = -8$ dptr., the refracting power in this case will be $F = 61.64$ dptr. Moreover, if the height of the object is 1 cm., the size of the retinal image will be found to be $y' = -1.49$ mm. (the minus sign meaning merely that the image on the retina is inverted). On the other hand, for an axially hypermetropic eye of $+5$ dptr., we find that $F = (63.64 - U)$ dptr.; and for an infinitely distant object ($U = 0$), the refracting power of this eye will be $F = 63.64$ dptr.

In case the object is infinitely distant, the size of the retinal image will be found to be

$$y' = \frac{F}{\omega}, \qquad (U = 0), \tag{6}$$

where ω, measured in radians, denotes the apparent size of the object, that is, the visual angle subtended at the eye by the distant object. This image on the retina is always inverted, so that the value of y' as found by this formula will be negative, which means that the angle ω must be reckoned as negative.

For the nodal points of an optical system, the magnification-ratio is equal to the ratio of the indices of refraction of the first and last media; and if in equations (3) we put $\mathrm{m} = n/n'$, we shall derive the image-equations referred to the nodal points.

In general, however, the difficulty about applying equations (3) to the optical system of the eye is that not only do the positions of the reference-points O, O′ vary during accommodation, but the magnification-ratio m varies also. The principal points of the eye, as we saw, remain very nearly stationary and the magnification-ratio for this pair of conjugate points is constant ($\mathrm{m} = +1$); so that for this special pair of conjugate points the above objections do not apply. And this is the reason why the image-equations referred to the principal points are used most often in modern ophthalmological writings. To be sure, it would be quite possible to locate other pairs of conjugate points on the axis which have precisely the same positions in both minimum and maximum accommodation, but it would be quite remarkable to find a pair of such points for which the magnification-ratio was constant also.

In this connection Dr. A. Gleichen* has recently called attention to the peculiar location and importance of the centre **K** of the pupil of the eye, which determines the positions of the centres **C**, **C′** of the entrance-pupil and exit-pupil of the eye. The entrance-pupil is the image of the pupil which is seen when we look into the eye, the so-called "black of the eye;" and since this image is formed by the cornea alone, which has nothing to do with the process of

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*A. Gleichen: Beitrag zur Theorie der Sehscharfe: *Graefes Archiv für Ophthalmologie*, 93 (1917), 303-356. This is a valuable contribution to this subject, and many of the ideas which it contains are incorporated in the present paper.

accommodation, it is obvious that if the pupil itself is stationary the entrance-pupil will remain stationary also. The centre **K** of the pupil is practically coincident with the vertex of the anterior surface of the crystalline lens when accommodation is relaxed entirely; and although the plane of the pupil is pushed slightly towards the cornea when the lens protrudes through the pupil in accommodation, the displacement is so minute that it may be entirely disregarded. Consequently, the points designated by **K** and **C** may both be considered as fixed points in the optical system of the eye. On the other hand, the exit-pupil with its centre at **C′** is the image of the pupil of the eye cast by the lenticular system; but here again since the modification of the lens which takes place during accommodation is confined almost entirely to the change of curvature of the anterior surface, and since the pupil is practically in contact with this surface, its image in the lens as a whole is scarcely affected at all by accommodation; and consequently the point **C′** may likewise be regarded as stationary. Moreover, if the diameters of the entrance-pupil and exit-pupil are denoted by $2p$ and $2p'$, while these diameters will vary, of course, with the involuntary contraction and dilatation of the pupil itself, the ratio $\mathrm{m} = p'/p$ will not be affected; and, moreover, by actual calculation it is found that this ratio m likewise remains practically constant during the whole process of accommodation. For example, using the data of Gullstrand's schematic eye, and assuming that the centre **K** of the pupil coincides with the position of the vertex of the anterior surface of the lens with accommodation relaxed, that is, putting **AK** = +3.6 mm., we shall find the following positions of the centres **C**, **C′** of the entrance-pupil and exit-pupil and the following values of the magnification-ratio with respect to these points:

Accommodation relaxed: **AC** = +3.05 mm.,
AC′ = +3.67 mm., m = +0.909;

Accommodation maximum: $\mathbf{AC}_{\max} = +3.05$ mm., $\mathbf{AC'}_{\max} = +3.65$ mm., $\mathrm{m}_{\max} = +0.917$.

Thus, acccording to this calculation, the points **C**, **C′** are indeed more nearly stationary than the principal points themselves; and since for them also the magnification-ratio is sensibly constant ($\mathrm{m} = +0.91$, say), they have the necessary qualifications of points of reference and for certain questions connected with the visual acuity of the eye they will be found to possess for this purpose distinct advantages, as Gleichen has pointed out in the paper mentioned above.

Let us put $\mathbf{CM} = z$, $Z = n/z = 1/z$, and $\mathbf{HC} = \boldsymbol{e}$; in which case we can easily obtain a formula showing the connection between the refraction of the eye (U) as measured from **H** and its refraction (Z) as measured from **C**. For since $\mathbf{HC} = \mathbf{H}\mathrm{M} + \mathrm{M}\mathbf{C}$, we must have:

$$\boldsymbol{e} = \frac{1}{U} - \frac{1}{Z},$$

and consequently:

$$Z = \frac{U}{1 - \boldsymbol{e} \cdot U}, \qquad U = \frac{Z}{1 + \boldsymbol{e} \cdot Z}. \tag{7}$$

Since in Gullstrand's schematic eye $\boldsymbol{e} = 0.0017$ m., the difference between U and Z is almost inappreciable. For example, when the eye is accommodated for a point 10 cm. away, that is, for $U = -10$ dptr., we find $Z = -9.83$ dptr.; and for more distant objects, the agreement will be still closer.

The image-equations referred to the centres **C**, **C′** of the entrance-pupil and exit-pupil may be put in the following forms:

$$\mathrm{m}^2 \cdot \boldsymbol{Z'} = Z + \mathrm{m} \cdot F, \qquad \mathrm{m} \cdot y' \cdot \boldsymbol{Z'} = y \cdot Z, \tag{8}$$

where $\boldsymbol{Z'} = n'/\boldsymbol{z'}$, $\boldsymbol{z'} = \mathbf{C'B}$, and $\mathrm{m} = +0.91$.

When accommodation is relaxed entirely, the above equations are modified as follows:

$$\mathrm{m}^2\cdot\boldsymbol{Z}' = \boldsymbol{Z} + \mathrm{m}\cdot\boldsymbol{F}, \qquad \mathrm{m}\cdot y'\cdot\boldsymbol{Z}' = y\cdot\boldsymbol{Z}, \tag{8a}$$

where $\boldsymbol{Z} = n/\boldsymbol{z} = 1/\boldsymbol{z}$ denotes the static refraction of the eye measured from the centre of the entrance-pupil **C** and $\boldsymbol{z} =$ **CR** denotes the far-point distance measured from the same origin.

In general, therefore, corresponding to formulæ (5), we have here the following useful relations:

$$\boldsymbol{Z} - Z = \mathrm{m}\ (F - \mathbf{F}), \qquad \frac{y'}{y} = \frac{\mathrm{m}\cdot Z}{\boldsymbol{Z} + \mathrm{m}\cdot\boldsymbol{F}} \quad . \tag{9}$$

Thus, for example, if an emmetropic eye ($\boldsymbol{Z} = 0$) is accommodated to see distinctly an object-point M, its refracting power will be $F = \boldsymbol{F} - Z/\mathrm{m}$, and the size of the image on the retina will be $y' = y\cdot Z/\boldsymbol{F}$.

5. Apparent Size of Object

The apparent size of an object as seen by the eye is measured by the angle ω which the object subtends at the eye. If $y = \mathrm{MQ}$ (Fig. 6) denotes the height of the object, and if $z = \mathrm{OM}$ denotes its distance measured from some

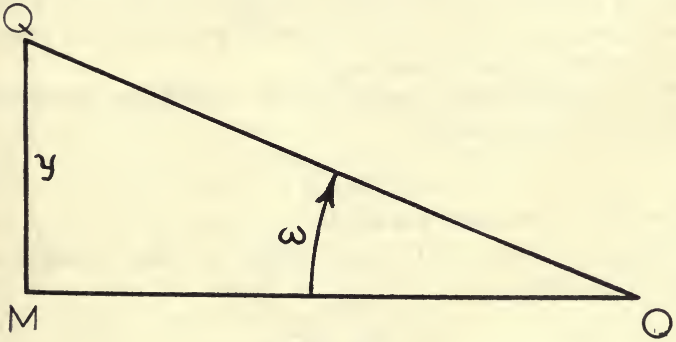

FIG. 6

APPARENT SIZE OF OBJECT

MQ = y, ∠MOQ = ω

definite point O connected with the eye, the angle ω is the acute angle MOQ supposed to be generated by revolving the line MO until it comes into coincidence with the straight line QO; this angle being reckoned positive or negative according as the rotation is counter-clockwise or clockwise, respectively. Thus for a real object in front of the eye the angle ω is negative, as represented in the diagram. Since the immobile eye can see distinctly at one time only a comparatively minute portion of an extended object, and since the symbol y as used here has reference merely to the part of the object which is sharply in focus on the most sensitive portion of the retina, the magnitudes y and ω are both small; and in place of the trigonometric tangent of the angle we may write the angle ω itself, provided its value is given not in degrees but in radians. Accordingly, if $Z=n/z=1/z$, we have in general:

$$\omega=y\cdot Z.$$

As long as the object lies at a considerable distance from the eye, it will not matter much what point O is selected as the vertex of the angle ω; but when the point M is comparatively close to the eye (as is often necessary for distinct vision), it becomes quite important to define precisely the position of the vertex of the visual angle.

The principal-point angle is the $\angle$M**H**Q $=\omega_H$ which is defined by the relation

$$\omega_H=y\cdot U, \tag{10}$$

where $U\cdot u=n=1$ and $u=$ **H**M.

Similarly, the pupil-centre angle is the $\angle$M**C**Q $=\omega_C$ defined as follows:

$$\omega_C=y\cdot Z, \tag{10a}$$

where $Z\cdot \mathbf{z}=n=1$ and $\mathbf{z}=$ **C**M.

Finally, the focal-point angle is the angle MFQ $=\omega_F$ defined by the relation:

$$\omega_F = y \cdot X, \qquad (10b)$$

where $X \cdot x = n = 1$ and $x = \text{FM}$.

6. Connection between the Apparent Size of the Object and the Image on the Retina

If a ray of light is directed from the highest point Q of the object towards the first focal point F of the eye (Fig. 7), after entering the eye it will emerge finally into the vitreous humour in a direction parallel to the optical axis and will meet the retina in the point Q′ which is conjugate to Q; assuming, of course, that the eye is accommodated to focus the image sharply on the retina, and assuming also that the object-point Q is so near the axis that the ray is a paraxial ray. If the point where the straight line QF crosses the first principal plane of the eye is designated by W, then evidently the size of the image on the retina will be $y' = \text{BQ}' = \text{HW}$; but the ratio **HW** : **FH** is equal to the tangent of the angle **HFW**, and this angle is equal to the focal-point angle $\omega_F = \angle\text{MFQ}$; and since as has been said we can write ω_F itself in place of tan ω_F, and moreover since $\text{F}\mathbf{H} = f = n/F = 1/F$, we obtain finally:

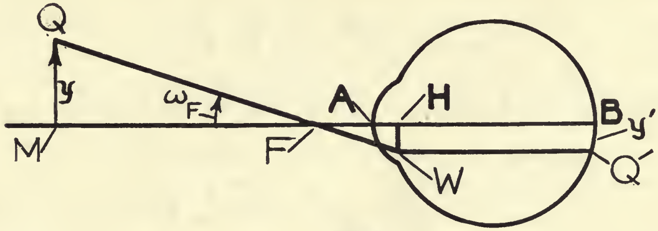

FIG. 7

APPARENT SIZE OF OBJECT AND SIZE OF IMAGE ON RETINA

$$\omega_F = y' . F'$$

$$\omega_F = y' \cdot F. \qquad (11)$$

Combining this result with the first of formulæ (5), we have also the following expression for the focal-point angle in terms of the static refraction of the eye:

$$\omega_F = (\boldsymbol{A} + \boldsymbol{F} - U)\, y'. \tag{11a}$$

Similar expressions may be obtained also for the principal-point angle (ω_H) and the pupil-centre angle (ω_C); for since

$$y \cdot U = y' \cdot \boldsymbol{A}', \qquad y \cdot Z = \mathrm{m} \cdot y' \cdot \boldsymbol{Z}',$$

we may write immediately:

$$\omega_H = y' \cdot \boldsymbol{A}' = (\boldsymbol{A} + \boldsymbol{F})\, y' \tag{12}$$

and

$$\omega_C = \mathrm{m} \cdot y' \cdot \boldsymbol{Z}' = \left(\frac{1}{\mathrm{m}} \boldsymbol{Z} + \boldsymbol{F}\right) y'. \tag{13}$$

These various results may be combined as follows:

$$y' = \frac{\omega_H - \omega_F}{U} = \frac{\omega_H - \omega_C}{\boldsymbol{A} - \frac{1}{\mathrm{m}} \boldsymbol{Z}} = \frac{\omega_F - \omega_C}{\boldsymbol{A} - \frac{1}{\mathrm{m}} \boldsymbol{Z} - U},$$

and also:

$$\omega_H : \omega_F : \omega_C = (\boldsymbol{A} + \boldsymbol{F}) : (\boldsymbol{A} + \boldsymbol{F} - U) : \left(\frac{1}{\mathrm{m}} \boldsymbol{Z} + \boldsymbol{F}\right).$$

We have therefore the following expressions for the size of the retinal image:

$$y' = \frac{\omega_H}{\boldsymbol{A}'} = \frac{\omega_F}{\boldsymbol{F}} = \frac{\omega_C}{\mathrm{m} \cdot \boldsymbol{Z}'}. \tag{14}$$

Thus in the case of a given individual the size of the retinal image is directly proportional to the visual angle (ω_H) subtended by the object at the first principal point of the eye, and it is entirely independent of the state of accommodation of the eye; so that no matter how the eye is accommodated, if the apparent size of the object as measured from the first principal point remains constant, the size of the corresponding distinct image on the retina will be constant also. The principal-point angle is therefore a measure of the size of the retinal image of one and the same eye when it is accommodated for distinct vision.

But for a given value of the refracting power (F), the size of the image (y') on the retina is proportional to the focal-point angle (ω_F); so that, for example, if it is desired to compare the retinal images of two different individuals whose eyes are accommodated so that their refracting powers are equal, it would be necessary merely to determine the ratio of the visual angles as measured by ω_F. If the focal-point angle has the same value for two different states of accommodation of one and the same eye, the size of the retinal image will be inversely proportional to the refracting power (F). When accommodation is relaxed entirely, so that F has its minimum value $\boldsymbol{F}$, the object will be situated at the far point **R**; and in this case the size of the retinal image will be $y' = \omega_F / \boldsymbol{F}$, where $\omega_F = \angle \mathbf{RFQ}$. Now if we are concerned only with such eyes as differ from each other merely in the lengths of their eyeballs (axially emmetropic or ametropic eyes, which are by far the most common cases), the value of $\boldsymbol{F}$ is the same for them all ($\boldsymbol{F} = 58.64$ dptr., as in Gullstrand's schematic eye); and therefore with relaxed accommodation the retinal images will be proportional to the visual angles as measured at the focal point **F**.

7. The Size of the Retinal Image of an Object Seen Through a Spectacle Glass

If a lens of negligible thickness is placed in front of the eye with its optical centre at a point L (Fig. 6), and if an object PE placed at P on the common axis of the two systems is viewed through the lens, the eye must be accommodated now to see distinctly the image MQ $= y$ of the object PE which is formed by the lens. Since the points L, E, Q are collinear, the apparent size of the object and of its image in the lens as measured from the optical centre of the lens will be the same; that is, $\omega_L = \angle \text{PLE} = \angle \text{MLQ}$. If the position of the first focal point of the eye when it is accommodated to see distinctly the image in the lens is designated by F, and if the position of the first principal point of the eye is designated by **H**, then we may write:

$$\omega_L = \frac{\text{MQ}}{\text{LM}} = \frac{\text{MQ}}{\text{LF}+\text{FM}} = \frac{\text{MQ}}{\text{L}\mathbf{H}+\mathbf{H}\text{M}} \quad ;$$

and if here we employ the following symbols:

$$u = \mathbf{H}\text{M},\ x = \text{FM},\ u \cdot U = x \cdot X = n = 1,\ t = \text{LF},\ c = \text{L}\mathbf{H},$$

the above relations may be expressed as follows:

$$\omega_L = \frac{y \cdot X}{1 + t \cdot X} = \frac{y \cdot U}{1 + c \cdot U} \quad . \tag{15}$$

Moreover, if $y' = \mathbf{B}\text{Q}'$ denotes the size of the image on the retina of the eye, then

$$y \cdot X = y' \cdot F, \qquad y \cdot U = y' \cdot \boldsymbol{A}',$$

and hence:

$$\frac{y'}{\omega_L} = \frac{1 + t \cdot X}{F} = \frac{1 + c \cdot U}{\boldsymbol{A}'} \quad . \tag{16}$$

If, for example, the lens is placed in the primary focal plane of the eye, that is, if $t = 0$ and $c = f$, then $\omega_L = \omega_F$ and $y' = \omega_F / F$, so that for this special position of the lens the retinal image with the lens will have the same size as the retinal image of an object MQ without any lens at all. Or, again, suppose that the object-point P is infinitely distant, then M will coincide with the second focal point (F'_1) of the lens; and if under these circumstances, accommodation is relaxed entirely, then the far point of the eye (**R**) will coincide with the second focal point of the lens; and then the lens is called a *correction-glass*.

8. Resolving Power and Visual Acuity of the Eye

In Robert Smith's celebrated *System of Compleat Opticks* (Cambridge, 1738) he states (Vol. I, Book I, Chap. 3, section 97) that "Dr. Hook assures us that the sharpest eye cannot well distinguish any distance in the heavens, suppose a spot of the moon's body, or the distance of two stars, which subtend a less angle at the eye than half a minute; and that hardly one of a hundred men can distinguish it when it subtends a minute." Incidentally, concerning this famous datum of Robert Hooke's (1705), it may be particularly noted that comparatively few individuals are capable of such high visual discernment as is here indicated; for example, Aubert, who was a very fine observer, was able under favourable conditions, and then only for a brief space of time, to distinguish with his naked eye the components of a double star whose angular interval amounted to $3' \, 30''$.

Nevertheless, it is generally assumed that when the visual angle subtended by an object becomes as small as one minute of arc or less, the object ceases to have apparent form, size or character of any kind and can no longer be distinguished from a mere point. Practically, since $\tan 1' = 1/3438$, this means, therefore, that the details of any object whose distance from the eye is 3438 times as great as its greatest diameter cannot be perceived by an average, so-called normal unaided eye. For example, if the object is 2 km. away, details (of form, colour, etc.) comprised within a circular area of about 58 cm. in diameter will be completely unrecognizable.

That the area covered by the smallest retinal image must indeed be very minute, is evident from the fact that it is comparatively easy for most people to perceive the width of the finest hair held at arm's length. On the assumption that the focal length of the eye is 17.1 mm. and that the angle subtended at the nodal point by the smallest perceptible image on the retina is exactly equal to one minute of arc, the computed diameter of the image will be found to be about 0.0049 mm.; which is not far from the average diameter of a retinal cone in the most sensitive part of the retina as ascertained by careful microscopic measurement. This rather striking agreement between the calculated value of the size of the smallest retinal image and the measured value of the diameters of the macular cones appears to support the theory which is very widely entertained that each single cone has its own separate nerve fibre leading direct to the visual centre in the brain, whereby the sensation excited in one cone is registered by itself and can therefore be distinguished from similar sensations produced in adjacent cones; and that, therefore, two luminous points will be seen as separate and distinct only in case their retinal images are far enough apart to affect more than one single cone or visual element of the retina. While this may be true, yet, as a matter of fact, the questions which are here involved are by no means so simple or so easily disposed of as calculations based on this theory more or less tacitly assume; and it may be pointed out that in such an intricate investigation as the complete determination of the distribution on the retina of the energy emanating from a point-source, not only are the methods and assumptions of geometrical optics alone entirely inadequate for this purpose, but the spherical and chromatic aberrations which are both very considerable in the optical system of the eye play an important part in the production of the resultant effect and cannot be ignored The theory that the smallest retinal image is confined to a single visual element of the retina is plausible and attractive but can by no means be regarded as established.

The *resolving power of the eye* is measured by the angle σ subtended at the eye by the interval between two object-points which are so near together that they can just be recognized as separate and distinct. This limiting angle is sometimes called the "angle of distinctness." The resolving power of the eye must not be confounded with its *aligning power*, which latter is a measure of the ability of the eye to judge, for example, whether two intersecting line-segments together form a single continuous straight line, or whether a mark on a vernier scale coincides exactly with an opposite mark on the main scale. This faculty is generally very much higher than the ordinary resolving power of the eye. In making an observation with a coincidence range-finder where two partial images in the field of view have to be adjusted relatively to each other so as to form a complete whole, the normal aligning power of the eye is considered to be 12 seconds of arc; and many individuals are able to exceed this value.

If the eye is able to distinguish as separate two object-points whose angular interval apart does not exceed a certain limiting value, it has been generally assumed in making test-charts for measuring visual acuity that an equal visual angle would be required in order to make out clearly the parts and distinguishing features of printed characters, letters, figures, etc.; but this is a mistake, inasmuch as entirely special factors are involved in the discrimination of such characters. Strictly speaking, such a test is not simply a question of the resolving power of the eye but of what may be described as the fineness of the space-sense, which admits of essentially finer distinctions than the resolving power alone. It should be borne in mind, therefore, that when the letters on the chart are constructed on the basis of the limiting angle as found for distinguishing two points, so that the characteristic parts of the letter are designed to subtend an angle of 1′ at a certain distance from the eye, the measurements obtained are in reality determinations of something that is not precisely the same thing as the visual acuity determined by a test with two single points; nor is it surprising, therefore, that different results are obtained with letters of different forms.

The oculist or optometrist is often satisfied provided he finds that his patient has normal or unit visual acuity as indicated by the numerical value marked on the chart; but the normal value is usually essentially higher than this conventional value of the visual acuity, and the investigation should always be pursued until the maximum visual acuity has been definitely ascertained. Accordingly, also, the interval or step between one line of letters on the chart and the next should not be too great; otherwise, the effect of the change of correction will not be clearly indicated. In this respect the charts arranged according to the decimal system of enumeration have an advantage over the ordinary Snellen's chart, since in the former there are four intermediate steps between the visual acuity corresponding to 0.5 and that corresponding to 1.0, whereas in the latter there is only one step between 6/12 and 6/6. In order to get the best results with the decimal chart, it should be hung about 7 or 8 metres from the patient, and then the value of the visual acuity given by the decimal fraction must be multiplied by the actual distance of the chart from the eye and this product divided by the distance for which the chart-numbers are calculated. Undoubtedly the visual acuity test-object of Ives has much to recommend it.

After this preliminary survey, we may proceed now to define more precisely the ideas that are connected with resolving power and visual acuity. If, for example, the vertex of the angle σ is chosen at some point S (Fig. 8) on the optical axis of the eye, and if M designates the point where the axis meets the object, and if D designates an object-point off the axis which can just be distinguished from M ($\angle$SMD $=90^\circ$), and moreover if we put $\angle$MSD $=\sigma$, $v=$ SM, $v.V=n=1$, and $y_0=$ MD, then

$$\sigma=y_0\cdot V. \tag{17}$$

And in the special case when the object is infinitely remote, we shall find that

$$\sigma=y'_0\cdot F, \qquad (V=0), \tag{17a}$$

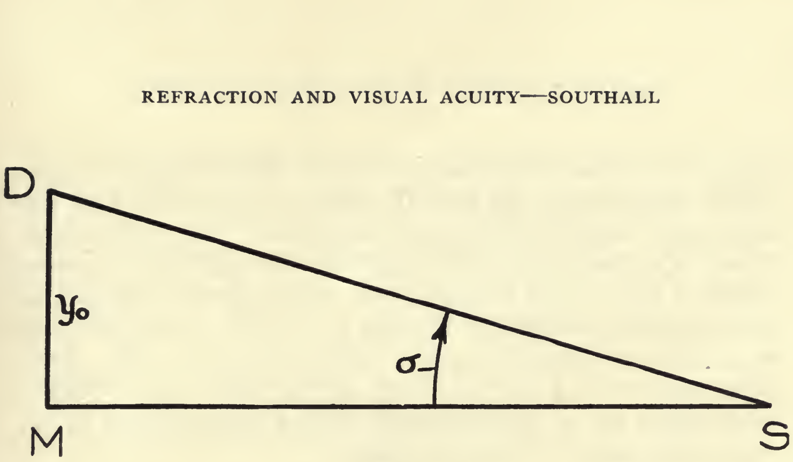

FIG. 8

where y'_0 denotes the size of the smallest retinal image and F denotes the refracting power of the eye when it is accommodated for focusing parallel rays on the retina.

The visual acuity of the eye (Σ) is inversely proportional to the resolving power (σ), so that the smaller the angle σ the greater the visual acuity Σ, and *vice versa*; and hence we may write:

$$\Sigma = -\frac{k}{\sigma} = -\frac{k}{y_0 V}\quad , \tag{18}$$

where k denotes here a numerical constant, the magnitude of which will depend on how unit visual acuity is defined. Usually, we say that the visual acuity is equal to unity when the angle σ is equal to 1′; and since this angle must be expressed here in radians, and since $1' = 0.000291$ radian, by putting $\Sigma = 1$ and $\sigma = -0.000291$ in the formula above, we obtain for the value of the constant k under these conditions:

$$k = 0.000291.$$

If the vertex S of the angle coincides with the first principal point of the eye (**H**), then substituting $U = V$, we shall write for this case:

$$\Sigma_H = -\frac{k}{\sigma_H} = -\frac{k}{y_0 \cdot U} = -\frac{k}{y'_0 \cdot A'}; \tag{19}$$

where y'_0 denotes the size of the smallest retinal image, which depends on the sensitiveness of the retina and has a constant value for a given individual. The function $\boldsymbol{A'}$ which is a measure of the length of the eyeball is likewise constant for one and the same eye; and therefore the *natural visual acuity* (as Gullstrand calls it), which is denoted here by Σ_H, and which is measured with respect to the first principal point of the eye in terms of the angle $\sigma_H = \angle \mathrm{MHD}$, is constant for a given individual and independent therefore of the state of accommodation.

Suppose that the eyes of two different individuals are alike in every way except that their eyeballs are unequally long. With relaxed accommodation they have, therefore, the same refracting power ($\boldsymbol{F}$), and with equally sound and sensitive retinas, the value of y'_0 will be the same for both eyes. Thus, their natural visual acuities will be inversely proportional to the function $\boldsymbol{A'} = (\boldsymbol{A} + \boldsymbol{F})$, where the value of the static refraction $\boldsymbol{A}$ is different for the two eyes. Suppose one eye is emmetropic so that for this eye $\boldsymbol{A} = 0$, whereas the other eye is axially ametropic; then according to the above, the visual acuity of the emmetrope will be to that of the ametrope in the ratio $(\boldsymbol{A} + \boldsymbol{F}) : \boldsymbol{F}$. For example, a hypermetrope ($\boldsymbol{A} > 0$) will not see as well at a distance as an emmetrope; whereas a myope ($\boldsymbol{A} < 0$) will see an object within his range of accommodation better than an emmetrope can see it at the same distance.

In the next place let us suppose now that the vertex S of the angle σ coincides with the first focal point (F) of the eye, and put $\angle \mathrm{MFD} = \sigma_F = y_0 \cdot X$, where $x = \mathrm{FM}$ and $x \cdot X = n = 1$. Accordingly, for this case we shall have:

$$\Sigma_F = -\frac{k}{\sigma_F} = -\frac{k}{y_0 X} = -\frac{k}{y'_0 \cdot F}; \qquad (20)$$

where F denotes the refracting power of the eye when it is accommodated for the object-point M. This function Σ_F is called by Gullstrand the *absolute visual acuity*; and it does not remain constant for a given individual but depends on the state of accommodation of the eye and is inversely proportional to the refracting power. Thus, for example, when the accommodation is relaxed entirely and M coincides with the far point (**R**), then $\Sigma_F = -k/y'_0 \cdot \boldsymbol{F}$; and when accommodation is a maximum and M coincides with the near point (**P**), then $\Sigma_F = -k/y'_0 \cdot \boldsymbol{F}_{\text{max.}}$ When it is desired to compare the visual acuity of one eye with that of another, if it may be assumed that the refracting power is the same for both eyes, the visual acuities will be inversely proportional to the values of σ_F (or of y'_0).

Finally, let us suppose that the vertex S of the angle σ is at the centre **C** of the entrance-pupil of the eye, and put $\angle \text{MCD} = \sigma_C = y_0 \cdot Z$, where $z = \text{CM}$ and $z \cdot Z = n = 1$; and hence

$$\Sigma_C = -\frac{k}{\sigma_C} = -\frac{k}{y_0 \cdot Z} = -\frac{k}{m \cdot y'_0 \cdot \boldsymbol{Z}'} \quad . \qquad (21)$$

These various measures of the visual acuity in one and the same eye may be compared as follows:

$$\Sigma_H : \Sigma_F : \Sigma_C = \frac{1}{U+F} : \frac{1}{F} : \frac{1}{\frac{1}{m}Z+F} \quad . \qquad (22)$$

For example,

$$\Sigma_F = \Sigma_H\left(1 + \frac{U}{F}\right) = \Sigma_C\left(1 + \frac{Z}{m \cdot F}\right) \quad . \qquad (22a)$$

9. Relative Visual Acuity with Spectacle Glass

If the object is viewed through a thin lens placed with its optical centre at a point L (Fig. 9) on the optical axis of the eye, the latter must be accommodated now to see distinctly the image of the object which is formed by the lens, and which may itself be considered as the object with respect to the optical system of the eye by itself. Let M designate

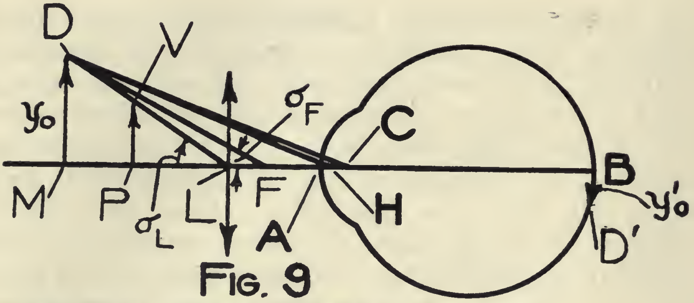

FIG. 9

RELATIVE VISUAL ACUITY OF EYE

MD $= y_o$ IS IMAGE FORMED BY LENS AT L OF, OBJECT PV IMAGE ON RETINA IS $y'_o =$ BD'

$\angle MLD = \sigma_L$, $\angle MFD = \sigma_F$

$\angle MHD = \sigma_H$, $\angle MCD = \sigma_C$

the position of the image-point which is conjugate with respect to the lens to an axial object-point at P. Draw MD perpendicular to the axis and suppose that the eye can just separate the two points M and D. The point of the object which corresponds to D is the point of intersection V of the straight line DL with the perpendicular to the optical axis erected at P. However, we may ignore the visible detail of the object PV altogether and confine our attention now to its image MD in the lens. The angle subtended at L by MD (or PV), which will be denoted by $\sigma_L = \angle MLD$ $(= \angle PLV)$ may be regarded as the measure of the resolving power of the combination of eye and lens; and if the distance of D from M is denoted by $y_o = MD$, then

$$\sigma_L = \frac{y_o}{LM} \quad .$$

The interval between the lens L and the eye, which of course must be known, may be assigned in various ways depending on the particular point of the eye which we have in mind. The distances from the lens of the first principal point of the eye (**H**), of the centre of the entrance-pupil (**C**), and of the first focal point of the eye (F) will be denoted by the symbols c, g and t, respectively; that is, $c = \mathrm{LH}$, $g = \mathrm{LC}$, $t = \mathrm{LF}$; and concerning these magnitudes it may be observed that for a given position of the lens and eye the values of c and g remain constant during accommodation, whereas the value of t varies. Moreover, the distance of the point M from the eye will be denoted as heretofore, that is, $u = \mathrm{HM}$, $z = \mathrm{CM}$, and $x = \mathrm{FM}$, where $u \cdot U = z \cdot Z = x \cdot X = n = 1$. Accordingly, in terms of these magnitudes the distance of M from L may be expressed in several ways as follows:

$$\mathrm{LM} = \frac{1 + c.U}{U} = \frac{1 + g \cdot Z}{Z} = \frac{1 + t \cdot X}{X} \quad ;$$

and consequently for the resolving power of the eye and lens together, we can write:

$$\sigma_{\mathrm{L}} = \frac{y_0.U}{1 + c.U} = \frac{y_0.Z}{1 + g \cdot Z} = \frac{y_0.X}{1 + t \cdot X} \quad . \tag{23}$$

The so-called *relative visual acuity* (Σ_{L}) of the reinforced eye is inversely proportional to the resolving power σ_{L}, that is,

$$\Sigma_{\mathrm{L}} = -\frac{\mathrm{k}}{\sigma_{\mathrm{L}}} \quad ; \tag{24}$$

and therefore we obtain the following expressions:

$$\Sigma_{\mathrm{L}} = -\frac{\mathrm{k}\ (1 + cU)}{y_0 \cdot U} = -\frac{\mathrm{k}\ (1 + g \cdot Z)}{y_0 \cdot Z} = -\frac{\mathrm{k}\ (1 + t \cdot X)}{y_0 \cdot X} \quad . \tag{25}$$

Comparing the above relations with the various expressions previously obtained for the visual acuity of the unaided eye as defined by Σ_{H}, Σ_{F} and Σ_{C}, we find:

$$\Sigma_{\mathrm{L}} = \Sigma_{\mathrm{H}}(1 + cU) = \Sigma_{\mathrm{C}}(1 + gZ) = \Sigma_{\mathrm{F}}(1 + tX). \tag{26}$$

If the refraction of the eye, measured by U, Z or X, is given in dioptries, the distances denoted by c, g and t will naturally have to be expressed in metres; but if these distances are given in centimetres, the second term in the parentheses of each of the expressions in (26) above must be divided by 100.

Generally, the lens is inserted in front of the eye not far from the first focal plane, so that the interval denoted by t either vanishes entirely or is relatively very minute; and, consequently, the relative visual acuity with the glass is not very different at most from the absolute visual acuity without the glass, that is, $\Sigma L = \Sigma F$, approximately if not exactly.

If the object is infinitely distant, then MD lies in the second focal plane of the lens, and the point M coincides, therefore, with the second focal point of the lens F'_1 (that is $MF'_1 = 0$); and when this is the case, the refracting power of the lens will be:

$$F_1 = \frac{U}{1 + c \cdot U} = \frac{Z}{1 + g \cdot Z} = \frac{X}{1 + t \cdot X}, \quad (MF'_1 = 0), \qquad (27)$$

and the relative visual acuity will be:

$$\Sigma L = -\frac{k}{y_0 \cdot F_1}, \quad \text{(infinitely distant object)}, \qquad (28)$$

where y_0 (which denotes the height of the image of the infinitely distant object formed in the second focal plane of the lens) must be reckoned positive for a concave glass and negative for a convex glass.

When the accommodation of the eye is relaxed entirely, then the point M will lie at the far point of the eye **R** ($M\mathbf{R} = 0$), and now we must put $U = \boldsymbol{A}$, $Z = \boldsymbol{Z}$ and $X = \boldsymbol{X}$; and if, also, the object is infinitely distant, that is, if $MF'_1 = M\mathbf{R} = 0$, under these conditions the lens is a so-called *correction-glass* ($F'_1\mathbf{R} = 0$), whose refracting power is:

$$F_1 = \frac{\boldsymbol{A}}{1 + c \cdot \boldsymbol{A}} = \frac{\boldsymbol{Z}}{1 + g \cdot \boldsymbol{Z}} = \frac{\boldsymbol{X}}{1 + t \cdot \boldsymbol{X}}, \quad (F'_1\mathbf{R} = 0). \qquad (29)$$

Accordingly, when the lens is a correction-glass of refracting power F_1, that is, when the object is infinitely distant and accommodation is entirely relaxed, we find:

$$\Sigma_L = \frac{\Sigma_H}{1 - c \cdot F_1} = \frac{\Sigma_C}{1 - g \cdot F_1} = \frac{\Sigma_F}{1 - t \cdot F_1};$$

and if c, g and t are expressed in centimetres, and F_1 in dioptries, we may write:

$$\left.\begin{aligned} \Sigma_H &= \Sigma_L\left(1 - \frac{c}{100}F_1\right); \\ \Sigma_C &= \Sigma_L\left(1 - \frac{g}{100}F_1\right); \\ \Sigma_F &= \Sigma_L\left(1 - \frac{t}{100}F_1\right). \end{aligned}\right\} \qquad (30)$$

Thus, having determined the refracting power F_1 of the correction-glass for given values of c, g and t, and having ascertained the relative visual acuity (Σ_L) with the glass, we can determine by means of the above formulæ the visual acuity of the naked eye, that is, the values of the functions denoted by Σ_H, Σ_C and Σ_F.

For example, if the relative visual acuity (Σ_L) has been ascertained by using a glass of power F_1 dioptries, which when placed at a distance of c centimetres from the first principal point of the eye enables the wearer to make out distinctly the details of the distant test-object, the natural visual acuity (Σ_H) of the naked eye may be found immediately, according to the first of the three formulæ (30), by diminishing the value of Σ_L by $c \cdot F_1$ per cent. (which means an actual increase when the lens is concave, since then $F_1 < 0$).

Or, again, since with relaxed accommodation ($U = A$) we can write:

$$\Sigma\mathrm{L} = \Sigma\mathrm{H}\left(1 + \frac{c}{100}A\right),$$

where c is given in centimetres, we can say that the visual acuity ($\Sigma\mathrm{L}$) of a passive ametropic eye with a correction-glass is greater than its natural visual acuity ($\Sigma\mathrm{H}$) without the glass by $c \cdot A$ per cent. (which means that the visual acuity of a myope for whom $A < 0$ will be less with a correction-glass than without it).

10. Indistinct Vision

Heretofore it has been consistently assumed that the eye was accommodated for an object-point M on the axis, and that the image of this point was therefore sharply in focus on the retina at **B**; and in such a case the visual acuity (except for diffraction effects which have been here left out of account) is independent of the pupillary opening.

But it often happens that the image of an object is not sharply focused on the retina, as, for example, when the axial object-point in question lies outside the range of accommodation, or when the attention of the observer is

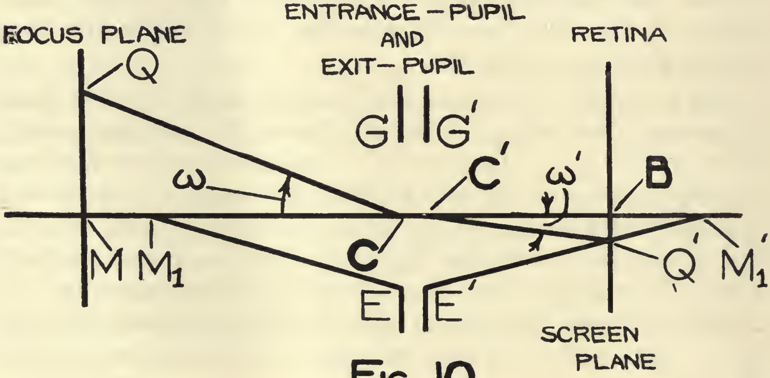

FIG. 10

INDISTINCT VISION

CASE WHEN $MM_1 > 0$

directed to some other point M_1 (or M_2) which is nearer to (or farther from) the eye than the point M for which it is accommodated, in which case the so-called image on the retina will be more or less blurred or indistinct; and the diameter of this *blur circle* (or circle of diffusion) will depend essentially on the diameter of the pupil of the eye.

In the accompanying schematic diagrams (Figs. 10 and 11) $EG = 2p$, $E'G' = 2p'$ represent the diameters of the entrance-pupil and exit-pupil of the eye whose centres are on the optical axis at the points designated by **C** and **C′**. The eye here is supposed to be accommodated for the axial object-point M, to which, therefore, the point **B** is conjugate, where the optical axis meets the retina. The two conjugate transversal planes at right angles to the optical axis at M and **B** may be called the *focus plane* and the *screen plane*, respectively. The latter is practically coincident with the retinal surface of the eye in its most sensitive region in the vicinity of the point **B**.

Consider now an axial object-point which does not lie in the focus-plane but which is either nearer the eye than M as M_1 in Fig. 10 ($MM_1 > 0$), or farther away, as M_2 in Fig. 11 ($MM_2 < 0$); so that the conjugate point M'_1 or M'_2 lies also to one side or the other of the point **B** on the retina. The intersection of the screen plane or surface of the retina with the cone of effective image-rays which proceeded originally from an axial object-point not in the focus plane will determine a blur circle with its centre at **B** the dimensions of which will depend on the distance of M_1 (or M_2) from M and on the diameter of the pupil of the eye. In fact the radius of this blur circle will be $y' = \mathbf{B}Q'$, where Q′ designates the position of the point where the straight line $E'M'_1$ in Fig. 10 (or $G'M'_2$ in Fig. 11) drawn from a point in the edge of the exit-pupil to M'_1 (or M'_2) crosses the retina. The diagrams are drawn here so that in both figures the point Q′ on the retina falls below the optical axis, and consequently the point Q in the focus plane which is the object-point corresponding to the image-point Q′ falls above the optical axis. A circular object lying in the focus plane with its centre at M and having a radius $y = \mathrm{MQ}$ would be imaged distinctly on the retina by a circle which would coincide with the blur circle that is actually produced there by the axial object-point M_1 (or M_2) which lies outside the focus plane.

Considering first the case represented in Fig. 10, we may write immediately the following proportion:

$$\frac{\mathbf{BQ'}}{\mathbf{C'E'}} = \frac{\mathbf{BM'_1}}{\mathbf{C'M'_1}} \quad ;$$

and if we introduce here the following symbols:

$$\mathrm{E}\mathbf{C} = \mathbf{C}\mathrm{G} = p,\ \mathrm{E'}\mathbf{C'} = \mathbf{C'}\mathrm{G'} = p',$$
$$\mathbf{CM} = z,\ \mathbf{C'B} = z',\ \mathbf{CM}_1 = z_1,\ \mathbf{C'}\mathrm{M'}_1 = z_1';$$

the relation above may be expressed as follows:

$$y' = -p'\ (1 - \frac{z'}{z'_1});$$

and hence, if also we put:

$$z \cdot Z = z_1 \cdot Z_1 = n, \quad z' \cdot Z' = z'_1 \cdot Z'_1 = n',$$

where n, n' denote the indices of refraction of the first and last media, we shall obtain the following expression for the diameter of the blur circle on the retina of the eye:

$$2y' = -\frac{2p'\ (Z' - Z'_1)}{Z'}\ ,$$

in which the diameter $2y'$ is reckoned always as negative, that is, is measured downwards merely because the image on the retina is inverted.

Now since

$$\mathrm{m}^2 \cdot Z' = Z + \mathrm{m} \cdot F, \quad \mathrm{m}^2 \cdot Z_1' = Z_1 + \mathrm{m} \cdot F,$$

where $\mathrm{m} = p'/p$, we have here:

$$\mathrm{m}^2\ (Z' - Z_1') = Z - Z_1;$$

and, moreover, since

$$m \cdot y' \cdot Z' = y \cdot Z,$$

by combining these relations with the formula for $2y'$ which was found above, the following expression may be obtained for the diameter of the corresponding circle in the focus plane:

$$2y = -\frac{2p\,(Z - Z_1)}{Z} \quad .$$

Draw the straight line QC making with the optical axis an angle which may be denoted here by ω; that is, the angle subtended at the centre **C** of the entrance-pupil by the radius ($y = \mathrm{MQ}$) of the circle in the focus plane which is conjugate to the blur circle on the retina is the angle $\mathrm{MCQ} = \omega$. Evidently, $\omega = y/z$ or $y \cdot Z = n \cdot \omega = \omega$, $(n = 1)$; and therefore according to the above we have for the case represented in Fig. 10:

$$2\omega = -2p\,(Z - Z_1), \quad (Z - Z_1) > 0. \tag{31}$$

Referring now to the other diagram (Fig. 11) in which M_2 is represented as being farther away from the eye than the focus plane, in this case we shall have:

$$\frac{\mathbf{BQ'}}{\mathbf{C'G'}} = \frac{\mathbf{BM'_2}}{\mathbf{C'M'_2}} \quad ,$$

and if here we put:

$$\mathbf{CM_2} = z_2, \quad \mathbf{C'M'_2} = z'_2, \quad z_2 \cdot Z_2 = n, \quad z'_2 \cdot Z'_2 = n',$$

we shall obtain precisely in the same way as above the following expression for the angular diameter of the circle in the focus plane:

$$2\omega = +2p\,(Z - Z_2), \quad (Z - Z_2) < 0. \tag{31a}$$

11. Focus Depth and Accommodation

The *focus depth* of an optical system (which, as everybody knows, is a matter of fundamental importance in a photographic lens, and which in the case of the eye is intimately associated with accommodation) is measured by the interval between a pair of transversal planes on opposite sides of the focus plane. The limiting position of each of these planes is determined by the fact that the blur circle in the screen plane corresponding to the axial object-point of either plane is so small that it can no longer be distinguished from a mere point. In the case of the optical system of the eye, let us suppose that when the eye is accommodated to see distinctly an object-point at M, the focus depth is measured by the segment of the axis comprised between the points M_2 and M_1 in Figs. 10 and 11. Then the points in the focus plane designated by M and Q are in reality so close together that the angle denoted above by 2ω is just equal to the resolving power of the eye; that is, $\sigma_C = 2\omega$; and accordingly for this special position of the pair of points designated by M_1 and M_2 we must have:

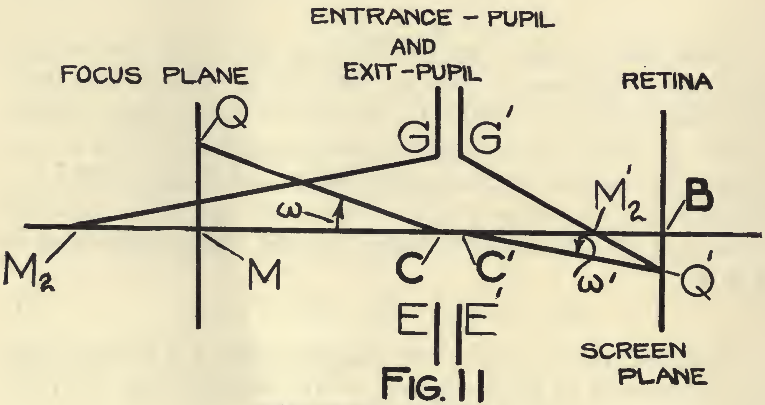

FIG. 11
INDISTINCT VISION
CASE WHEN $MM_2 < 0$

$$\sigma_C = -2p\ (Z - Z_1) = 2p\ (Z - Z_2), \qquad (32)$$

where

$$(Z-Z_1)>0>(Z-Z_2);$$

and if we put

$$D=-\frac{\sigma c}{2p}, \tag{33}$$

then

$$Z-Z_1=Z_2-Z=\frac{Z_2-Z_1}{2}=D. \tag{34}$$

Also,

$$D=\frac{k}{2p\cdot\Sigma c}; \tag{35}$$

and therefore the function D which is a measure of the focus depth is inversely proportional to both the diameter ($2p$) of the entrance-pupil and the visual acuity (Σc). The value of D increases, therefore, with decrease of the visual acuity of the eye. For ordinary daylight illumination the diameter of the pupil of the eye is about 3 mm., so that for convenience of calculation in the above formula we may put $2p=2.91$ mm., since the constant k has the value 0.000291. With these data we find, for normal visual acuity ($\Sigma c=1$), $D=0.1$ dptr.

It is easy to show that the linear measure of the focus depth in metres is:

$$M_2M_1=\frac{2D}{Z^2-D^2}. \tag{36}$$

Thus, for example, suppose the point M lies at the conventional distance of distinct vision, that is, 25 cm. from the eye ($Z=-4$ dptr.), and suppose that $D=0.1$ dptr., as found above; then $M_2M_1=$nearly 1/80 metre or nearly 1.25 cm. Or, again, suppose a person whose visual acuity is 0.5 is accommodated for a point 1 metre away ($Z=-1$ dptr.); if we assume, as above, that $2p=2.91$ mm., then $D=0.2$ dptr., and $M_2M_1=$nearly 21 cm. And if, everything else being the same as before, we had assumed that the visual acuity was equal to 1/3, we should have found $M_2M_1 = 66$ cm. These examples show how rapidly the focus depth increases with decrease of visual acuity of the eye.

12. Manifest Amplitude of Accommodation

The point on the optical axis of the eye which is sharply in focus when accommodation is relaxed entirely is the far point **R** according to the precise definition of this point; but the physiological far point $\mathbf{R_2}$ is a point which actually lies farther from the eye than **R** (Fig. 12). And, similarly, the physiological near point $\mathbf{P_1}$ is a point which lies nearer the eye than the real near point **P**. Thus, the so-called *manifest range of accommodation* $\mathbf{R_2P_1}$ is an extension of the real range of accommodation **RP** at both ends; and it is this manifest range of accommodation which is usually determined by actual subjective measurements. If we put

$$\mathbf{CR} = z,\ \mathbf{CR_2} = z_2,\ \mathbf{CP} = z_{\max},\ \mathbf{CP_1} = z_{1,\ \max};$$
$$z\cdot Z = z_2\cdot Z_2 = z_{\max}\cdot Z_{\max} = z_{1,\ \max}\cdot Z_{1,\ \max} = n = 1;$$

then

$$Z_2 - Z = Z_{\max} - Z_{1,\ \max} = D = \frac{\mathrm{k}}{2p\cdot\Sigma \mathrm{c}},$$

or

$$Z_2 - Z_{1,\ \max} = (Z - Z_{\max}) + 2D, \tag{37}$$

where $(Z - Z_{\max})$ is the measure of the real amplitude of accommodation (with respect to the centre of the entrance-pupil as origin), and $(Z_2 - Z_{1,\ \max})$ is the measure of the manifest amplitude of accommodation. In practical determinations of the amplitude of accommodation, either with test charts or lenses, it is usually this manifest amplitude of accommodation which is ascertained, as was stated above, and which is greater than the real amplitude by the magnitude denoted here by $2D$.

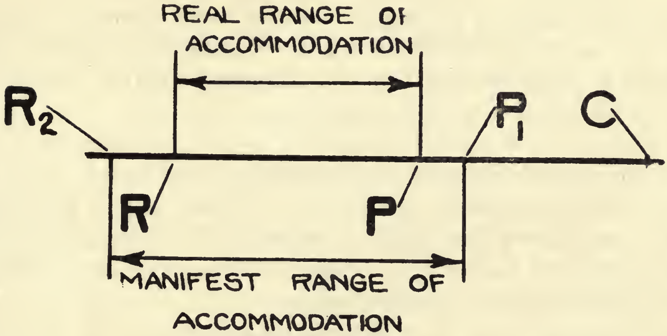

FIG. 12
RANGE OF ACCOMMODATION
REAL AND MANIFEST

Under ordinary circumstances the difference between the manifest amplitude of accommodation and the real amplitude does not usually amount to very much. For instance, with normal visual acuity ($\Sigma c = 1$) and with average pupillary opening ($2p = 2.91$ mm., say), we saw above that $2D = 0.2$ dptr., which would be almost inappreciable in the case of a young person with a considerable power of accommodation anyhow. But Gleichen, in his valuable paper already alluded to, points out that this function D is a quantity of an entirely different nature from the real amplitude of accommodation itself, which latter depends solely on the dioptric system of the eye, whereas the magnitude $2D$ which is the additional term which differentiates the manifest amplitude from the real amplitude depends both on the aperture ($2p$) of the optical system of the eye and on the visual acuity (Σ_C) or retinal efficiency of the eye. Thus, whereas the amplitude of accommodation diminishes with increasing years, the term $2D$ remains constant or else increases in value, inasmuch as we often find in old age both a contraction of the pupil and a decrease of visual acuity. Indeed, at a very advanced age, 60 years or more, the value of $2D$ may become so large that the total manifest amplitude of accommodation is quite considerable, amounting perhaps to more than a dioptry, although the real amplitude of accommodation may be exceedingly limited.

It should be remarked that within the manifest range of accommodation the visual acuity (Σc) is constant.

For an emmetropic eye ($\boldsymbol{Z}=0$) the far point **R** lies at infinity and the physiological far point lies beyond infinity, that is, behind the eye; so that such an eye may have a weak physiological hypermetropia.

In hypermetropia both **R** and $\mathbf{R}_2$ are behind the eye and the magnitudes denoted by $\boldsymbol{Z}$ and $\boldsymbol{Z}_2$ are to be reckoned as positive in this case.

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The Enigma of Color Vision

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I

THE process called vision by which we become aware of objects about us has been a subject of philosophical and scientific speculation for thousands of years. Even the Greeks had definite theories of its mechanism. The doctrines of Democrates, Anaxagoras, and other Greek thinkers, concerning the images which they supposed to be emanated from objects and picked up by the eye have developed in the course of centuries into the physical science known as optics. This science, which has in recent times become a sub-division of the universal science of electromagnetic phenomena, deals with the processes by which material objects are able to act upon the retina of the eye. It has long since attained the dignified status of an exact science and its fundamental laws and the character of the physical realities upon which they depend are very satisfactorily understood.

The Greeks recognized clearly that the form of consciousness of the external world which we call vision depends upon the eye, since when the eye is destroyed or when the action of objects upon it is obstructed one can no longer see. They did not know, however, what is now equally certain, that vision depends upon the activity of the optic nerve and that portions of the brain, particularly certain portions of the surface of the cerebrum, are necessary for the production of visual perception. Destruction of any of the links in the chain of nervous conduction which connects the eye with the higher centers of the brain is just as fatal to vision as is the interception of the light from objects before it reaches the eye. Our visual consciousness depends upon sight not only through the space between the eye and the object but through the entire optic nerve path between the brain and the eye. The mind looks through the optic nerve as through a telescope. Indeed the facts show that certain portions of the brain are more important for visual consciousness than are rays of light striking the eye, since we can *imagine* things visually without the aid of the latter but such imagination becomes impossible when the so-called visuo-psychic areas of the cerebral cortex are destroyed.

The question as to the exact manner in which vision depends upon the activities of the optic nervous mechanism has interested philosophical and scientific thinkers nearly as much as that of the nature of light, the stimulus of this activity. A very large number of speculative theories have been advanced to account for observed phenomena. Unfortunately, however, the science of *physiological optics*, which deals with this aspect of the dependency of visual consciousness upon material factors, has not reached the stage of development where it can be favorably compared with physical optics. Our so-called theories of vision are intellectually puny affairs compared with the theories employed in explaining the behavior of light. Some of the visual theories are very helpful as far as they go, but they do not go very far. As a rule, they account for the special group of facts with which they were expressly developed to deal but find difficulty in explaining some new discovery or some fact overlooked by the authors of the theories.

The cause of this unsatisfactory status of the science of physiological optics is easily found. In general, our understanding of the processes which go on in living organisms is at present very imperfect. The outlines of the major organic activities have been made very clear by the researches of the great physiologists of the eighteenth and nineteenth centuries and the twentieth century is witnessing a detailed development of our knowledge of many of these functions, including those of the nervous system. However, we know very little by direct observation concerning the operations of sense organs and their attached nerves. Moreover all biological activities appear to depend upon a vast complex of factors rather than upon a few simple conditions, as is usually the case with the phenomena considered by the sciences of inorganic nature. A further difficulty lies in the fact that physiological optics is obliged to deal with one of the most mysterious and perplexing facts which is open to our observation, namely that of the dependency of consciousness upon the processes of the nervous system. Not only is this relationship of an entirely different kind from that considered by any purely physical science, but the characteristics of consciousness are difficult to define and measure in any exact way.

It is not the purpose of the writer in the present paper to propound a new theory of color vision. Some of the cleverest scientific minds which have ever pondered upon the mysteries of the universe have produced such theories for our enlightenment, but when we see how unenlightening these theories actually are we cannot but feel modest and awe-stricken in the face of the fundamental problems of psychophysical optics. Vision seems to be a perpetual scientific enigma, the perfect solution of which is still far from our grasp. It is my purpose at present merely to state clearly some of the elements of the enigma, elements which are far more numerous and enigmatical today than they were in the days of Thomas Young or even of Helmholtz and Hering.

II

If we regard physiological optics as an effort to explain vision, in the ordinary sense of the term, we must start with the *visual consciousness*. This consciousness is identical with the dominant aspect of what common-sense thinking calls the external world. The world as it is presented to us is mainly visual, and as such is composed of colors (including grays) arranged in definite spatial patterns or mosaics. Color and space are the materials of which the visual consciousness is constructed. The total number of different colors which can be discriminated appears to be strictly limited. Although the number is large the similarities between colors permit them to be arranged into a fairly simple system within which certain colors stand out distinctively and become reference points for the system as a whole. These colors, as recognized by Leonardo da Vinci, Goethe, and other early students of the subject, are black, white, red, yellow, green, and blue. Theories of vision which fail to take into consideration the distinctive character of these six "psychological primaries" fail to meet one of the most primitive requirements laid upon such theories. All other colors can be intelligibly described in terms of these primaries—or their dominant qualities—but the latter cannot be intelligibly described in terms of any color qualities other than themselves. They may be divided into two groups, the first—including only black and white—being designated as *achromatic*, and a second—including the remaining four qualities—being called *chromatic*.

When we describe any color in terms of these psychological primaries we usually find it necessary to specify it in *three* ways. Every color, no matter what its quality, must be described in terms of its relation to either black or white. This relation determines its *luminosity* value or apparent brightness, the latter being at a minimum for black and at a maximum for white. There is only one color having zero luminosity, namely black itself, and it is probable that there is but one color of maximum luminosity, namely a "pure" white. At intermediate luminosity values, however, a variety of colors is possible. In the first place there is a single series of colors which appear to be determined wholly by their luminosity values and which are called grays. Like black and white they are achromatic in character. Corresponding to any given gray, and of the same luminosity, we find chromatic colors which may be described in terms of any one, or certain combinations of two, of the chromatic psychological primaries. The selection of the chromatic primary or primaries determines the *hue* of the color. It is not sufficient, however, to specify the luminosity and the hue alone, since a considerable number of discriminable colors having identical hues and luminosities can exist. These colors seem to vary in their degree of difference from the gray of the same luminosity. This degree of difference is known as their *saturation.*

The fundamental problem facing a theory of color vision lies in the explanation of the relations existing between the psychological primaries and their forms of combination in consciousness on the one hand and the activities of the optic nervous system on the other hand. Certain general characteristics which such a theory must possess should be clearly recognized at the outset. In the first place, the theory cannot be simple. Extant theories of vision have attempted to emulate physical theories by affecting an extreme simplicity of formulation and then purporting to explain a bewildering variety of phenomena by deductions from these simple assumptions. There can be no doubt that a simple theory is desirable for pedagogical purposes, but analogy with empirically established principles in physiology does not lead us to expect that simple assumptions can explain all the facts of color vision. The vital mechanisms are often even redundant in their complexities. The same end may be achieved simultaneously by a number of quite different processes. For example, the direct effects produced by excitation of the sympathetic nervous system are identical with those resulting from the secretion of adrenin into the blood, and both of these causes act simultaneously. We could explain the effects almost completely on the assumption that either one of the causes was operative alone, but our explanation would be in error. In the same way, in the case of vision it is likely that certain subjective phenomena which appear to be very similar can actually be the results of radically different physiological causes.

Another general characteristic of a visual theory, which pretends to be not merely a pedagogical device but a delineation of the actual mechanism of vision, must be its inclusion not only of processes occurring in the eye but of those which are located in the optic nerve and the brain centers to which the conductors of this nerve lead. There appears to be a tendency for theories of vision to over-emphasize the *retinal* factors in the process, whereas, as a matter of fact, it seems certain that the brain factors are those which are of cardinal importance. It is true that many theories—even that of Helmholtz as expressed in the second edition of his *Physiological Optics*—have considered the part played by the higher nervous connections of the retina. Usually, however, the attempt has been made to explain the majority of visual phenomena on the basis of retinal mechanisms.* The theorists have seemed to feel that they knew more about sense organ processes than they did about those of the sensory nerves or the central nervous system. They have taken the attitude that a function should be regarded as peripheral in origin until it is proven to be central.

In the light of our present knowledge, however, it appears very probable that this is a radical error. The visual consciousness depends primarily upon central nervous processes and only indirectly upon those of the retina. Even if we determine the correlates of the various psychological factors in the retina we have still to ascertain their correlates in the essential nervous centers, and the correlation in the latter case is apt to be more complete than in the former. Moreover, it is fortunate that recent advances in our knowledge of nerve functions have been so extensive that we now actually have more information about the nature of nerve fibre and nerve junction (synaptic) activities than we have about the processes which occur in the sense organs or receptors. The work of Lucas, Adrian, Nernst, and others on the physical basis of nerve excitation and the nerve impulse has given us a very considerable insight into these processes, while the investigations of Sherrington, Head, and others on the mechanisms of central adjustment in the nervous system throw a great deal of light on the nature of the synaptic or central nerve processes.

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* Hering side-steps this entire problem by using the term Netzhaut (retina) to designate the *entire visual* nervous system.

It is one of the purposes of the present paper to suggest certain lines of thought in regard to the mechanism of vision which depend upon the discoveries of some of the investigators mentioned above. The demonstration of the "all or none" principle by Adrian and Lucas has very important implications for the theory of vision, and the work of Sherrington, as recognized by that writer himself, contains many conceptions which have been an enlightening application to visual problems.

III

I possess, in my catalogue of visual literature, references to more than sixty different theories of the mechanism of visual response. Out of this large number of more or less independently conceived hypotheses, however, only three have proven sufficiently valuable to be discussed in the text books of psychology, physiology or physics. The three theories in question are those of Young (and Helmholtz), Hering, and Ladd-Franklin. The Young-Helmholtz theory is preferred by physicists because it lays emphasis primarily upon the stimuli to vision, while the Hering theory receives more attention at the hands of the psychologists because its fundamental conceptions are derived from introspective analysis. It is gratifying to note, however, that in a number of recent psychological texts the theory of Mrs. Ladd-Franklin has supplanted the other two theories as a pedagogical instrument, since it takes into account both sets of fundamental facts which the other theories were respectively designed to explain.

All three of these popular theories postulate the existence in the retina of a number of specific chemical substances which are acted upon by light. According to the *Young-Helmholtz theory* there are three of these substances, which are decomposed at maximal rates by red, green, and blue light respectively. These rates of decomposition are reported individually to the brain *via* the optic nerve and the ratio between the three values determines the character of the sensation. Some advocates of this so-called three component theory refuse to state it in terms of "substances" and formulate the doctrine in abstract terms. This is a convenient method of avoiding difficulties which appear when one attempts to develop the theory in more detail, but unfortunately, when thus expressed, the doctrine is no longer an explanation of anything, but merely a straightforward representation of certain well established experimental facts. In its less abstract form the Young-Helmholtz theory accounts satisfactorily for the laws of "color mixture" for normal, and also for some forms of color-defective vision, but it does very little more than this. It fails completely to explain the radical changes in the character of the colors which are experienced when certain ratios of the elementary processes are realized: for example, the combination of red and green to form yellow or of yellow and blue to form white.

The *theory of Hering* also postulates the existence in the *Netzhaut*—which includes the entire retino-cerebral apparatus—of three substances. One of these substances is decomposed by lights of all wave-lengths, although to the greatest extent by yellow-green light, and spontaneously builds itself up in the absence, or relative absence, of light. The other two substances are decomposed at a maximal rate by red and yellow lights respectively and are recomposed at maximal rates by green and blue lights respectively. The six psychological primary colors are correlated directly with these six distinctive rates of change occurring in the three substances; white with the decomposition of the first substance and black with its recomposition, red and green with corresponding changes in the second substance respectively, and yellow and blue in a similar way with the changes in the third substance. This system of relationships satisfactorily accounts for the manner in which the psychological primaries combine with one another, accounting especially for the "antagonistic" behavior of red and green, and yellow and blue. Negative and complementary after-image effects are also explained, at least qualitatively, and the facts of color mixture are represented as accurately, if at the same time somewhat redundantly, by this system as by that of the Young-Helmholtz theory.

Three serious objections must, however, be raised against the Hering theory in the form in which it was left by its author. Its assumption that anabolic (or constructive) processes can be brought about by the direct action of a stimulus has been severely criticized by Verworn and others, but it is certain that we do not know enough about the actual process in the retina to make any categorical assertions on this particular point. The three weakest points in the Hering theory appear to me to be: (1) the failure of opposite processes in the black-white substance actually to cancel each other, while those in the other two substances always leave a residual gray, (2) the fact that psychologically primary red and green do not in fact combine to produce a gray but rather a yellow, and (3) the failure of continuous stimulation of a single region of the retina to reduce the sensory effects of all stimuli to a neutral mid-gray.

The first difficulty has been discussed at great length by G. E. Müller, who differentiates between the processes occurring in the retina and those in the brain centers, placing the Hering substances in the former location and assuming the existence of an additional gray-producing process in the centers. This appears to meet the first difficulty, at least formally. In regard to the second objection, I am informed by Mrs. Ladd-Franklin that she has carried out experiments showing conclusively that psychological red and green always unite to produce a yellow rather than a neutral gray. The stimuli employed in her experiments were colored papers mixed on disks rather than spectral lights, so that the results are not affected by the assumption, which is in fact erroneous, that a physically pure spectral red produces a psychologically primary red sensation. There seems to be no simple modification of the original assumptions of the Hering theory which will remove this difficulty. The third objection is based upon very extensive investigations of my own upon the fatigue of the visual system, to stimuli of many different wave-lengths and intensities, during various periods of action. Hering's assumptions demand that complete exhaustion of any specific sensibility should finally be reached under all conditions, but my results indicate that such exhaustion occurs only under limited special conditions.

The only plausible manner in which to meet this third difficulty would appear to be to give up the cardinal characteristic of the Hering theory, namely the essentially antagonistic nature of the processes underlying respective members of the three pairs of primary colors. I have presented elsewhere a theory having the form thus suggested, in which five distinct light-sensitive substances are supposed to exist in the retina, each of these substances being decomposed by the action of light, the rate of decomposition being at a maximum at different wave-lengths for the different substances. One of the substances is responsible for white, while the remaining four determine the psychological primaries, red, yellow, green, and blue respectively. Black is represented by an unstimulated but not necessarily an inactive condition of the visual brain centers. This theory, however, is open to the second objection raised against the original Hering theory, and is also compelled to account for the antagonism of red with green and of blue with yellow by a special *ad hoc* assumption.

According to the *Ladd-Franklin theory* there is only a single light-sensitive substance in the retina. This substance, however, exists in three stages of evolution or differentiation. In the most primitive stage its decomposition by the action of light leads to the excitation of the optic nerve fibres in such a manner as to produce various gradations of achromatic luminosity in the visual sensation ranging from black, which is associated with the absence of excitation, to a white, associated with the maximal rate of decomposition. In the second stage of differentiation the substance presents to the action of light two separate parts coresponding, for example, with two different radicles involved in the constitution of its molecules. One of these parts is decomposed at the maximal rate by yellow light and the other part similarly by blue light, the separate products of these respective decompositions acting upon the optic nerve to produce the colors yellow and blue respectively in consciousness. Simultaneous and equivalent decomposition of the two parts of the substance, however, reproduces the original primitive form of stimulation of the optic nerve fibres and hence generates a gray in consciousness. The third stage of evolution of the substance involves a differentiation of the yellow-sensitive component into red-sensitive and green-sensitive constituents. When these are acted upon separately they produce a psychologically primary red and green in consciousness, but when simultaneously decomposed they yield the original yellow value.

It must be acknowledged that the system of explanation employed in the Ladd-Franklin theory is not only extremely ingenious but that its basic outlines are probably essential to any satisfactory elucidation of the visual process. It is true that red and green are antagonistic, as indicated by the Hering terminology, but the product of their conflict is not white but yellow. The yellow thus produced now comes into antagonism with blue and the outcome of this second conflict is a different quality, namely white or gray. The psychological primaries are thus arranged not into three coordinate pairs but into a hierarchy which has a definite form.

From the modern point of view the above outlined theories of color vision must probably be regarded as applying only to the mechanism of response of the retinal cones. The Young-Helmholtz and Hering theories were developed before it had become as certain as it now is that there are two distinct mechanisms of response in the retina, one—depending upon the cones—being predominant in day vision and yielding chromatic as well as achromatic sensations, and the other—depending upon the rods—replacing the cone response in twilight or evening vision and yielding only achromatic sensations. The so-called *duplicity theory*, which is concerned with this differentiation of functions, can now be regarded not as a speculative hypothesis but rather as an established fact. Von Kries, one of the modern exponents of the Young-Helmholtz theory, explicitly regards this latter theory as applying to the cones only, the rod process involving an additional mechanism. Hering and his school have apparently avoided any explicit recognition of the validity of the facts which differentiate the functions of the rods from those of the cones. I believe that Mrs. Ladd-Franklin conceives the essential light-sensitive material of the rods to correspond with the substance of her theory in its most primitive form, although it is not necessarily to be identified with the visual purple, a pigment which is found in the rods. This latter pigment may be simply a sensitizing agent acting in the rods much as certain dyes act in connection with the silver bromide of a photographic emulsion, picking up the light and passing it on to another photo-sensitive body.

If we regard the three color theories as being intended to account primarily for the psycho-physical response of the retinal cones and supplement any one of them by the assumption of an independent rod response for twilight vision I think it is clear that the Ladd-Franklin theory is distinctly superior to either of the other two. This theory establishes contact on the one hand with the psychologically primary color qualities and on the other hand it takes cognizance of the three-color-mixture laws upon which the Young-Helmholtz theory is based. However, although the theory is very beautiful as a pedagogical device I do not find it to be convincing as a picture of the actual process of color vision. In the first place, Mrs. Franklin's conception of the "evolution of a molecule" strikes me as being somewhat mythical. The evolution which her theory requires is one in which the ultimate decomposition products of the molecule remain unchanged, although these products become divisible into three portions which can be liberated from the original substance independently of one another. It is necessary to suppose that the original decomposition material had a threefold nature such that when properly divided it would become capable of producing the three or four chromatic qualities of color vision at its highest state of development. This seems an improbable supposition.

Assuming, however, the possibility of such a happy molecular evolution, I still find difficulty with Mrs. Franklin's explanation of the manner in which the several types of decomposition of the molecule determine their respective visual qualities in consciousness. The Ladd-Franklin theory is essentially a theory of the retinal process and it postulates definite chemical conditions, in the retina, for each of the psychologically primary colors. The condition for black is the absence of all decomposition products; for white, the presence of a maximal quantity of all (these being chemically combined); for red, green, and blue the presence of predominant quantities of those moieties of the decomposition material which are responsible for these three color qualities respectively, and for yellow the presence of a compound which is formed by the chemical union of the red-representing and green-representing bodies. These six distinctive chemical conditions must be supposed to generate six distinctive forms of excitation in the optic nerve fibres, although one of these "forms,"—*viz.* that for black—may be the absence of excitation. The fact that the red-representing and green-representing decomposition substances unite chemically is supposed to make it impossible for them to generate the types of optic nerve currents which are characteristic of them as uncombined individuals and to enable them to generate an entirely new type of nerve current which produces the color quality yellow, in consciousness. A similar relationship holds between all three chromatic decomposition materials in their combination to produce the white-representing substance which brings about its own characteristic type of nerve stimulation. It appears to me that the Ladd-Franklin theory postulates the existence in the retina of conditions of sensation of the sort required for the processes in the cerebral cortex which directly underlie the visual consciousness, but which are not required and probably do not exist in the case of the retina.

IV

The most primitive theories of vision regard the visual consciousness as determined directly by the object. Somewhat more sophisticated views make the retinal process the chief determinant of visual perception. A still more advanced conception would look upon the visual projection areas of the cerebral cortex as of prime importance. An even deeper analysis indicates that the cerebral processes which immediately determine the character of the visual consciousness probably lie in the so-called association areas of the cortex and that the exact form of the processes in these areas is dependent not only upon the manner of functioning of the three phases in the response already mentioned but also upon a series of processes which are interpolated between the association areas and the visual projection areas. The facts of pathology show that we are justified in postulating the existence in the cerebrum of highly elaborate visual mechanisms. There seems to be a special cerebral mechanism for almost every separable aspect of the optic function. The visual world, as it is given immediately in consciousness, is the product, so to speak, of an elaborate series of manufacturing operations. Cortical functions appear to be arranged in neurally superposed layers or strata and the introspective consciousness depends directly only upon the uppermost of these. It is only in the latter that we should expect to find the visual processes in exact parallelism with those of consciousness. The correspondence between consciousness and the operations in lower neural strata would be disturbed by the contributions made by intervening strata.

Pathological changes in the visual areas of the cerebral cortex are capable of causing profound modifications in color vision without equivalent effect upon other visual functions. Certain color functions, moreover, such as those of contrast, can remain operative when extensive lesions in the projection areas have practically severed the connection between the higher cerebral areas and the retina. This does not prove, of course, that there are no contrast producing mechanisms in the retina, but it does show that such mechanisms exist in the centers, so that the assumption of a retinal contrast mechanism is not necessary. Characteristic modifications in color vision due to pathological lesions in the visual cortex indicate the existence in the cortex of definite processes corresponding to the constituents of the visual consciousness. If we understood the exact manner in which consciousness depends upon these processes its relation to the retinal processes would develop as a mere physiological implication.

We may correctly assume that in the cortical process which immediately determines the visual consciousness there are six distinctive conditions or processes corresponding with the six fundamental psychologically primary color qualities, since introspection analytically describes all colors in terms of these fundamentals. The principles just considered, however, show that this assumption does not imply the existence of six corresponding processes in the retina, in the optic nerve function, or even in the visual projection areas of the cerebrum. Whether or not certain characteristic processes are set into operation in the region of the cortex which immediately determines consciousness may depend upon relations which are not of a simple point-to-point character. The arousal of such processes may be conditional upon complex quantitative relations with the magnitudes of a smaller number of variables in the nerve or retinal mechanisms, just as the selection of separate retinal processes must depend upon the single factor of stimulus wave-length. It is practically certain that an exact point-to-point correspondence cannot exist between the ultimate cerebral components of the visual process and its retinal components. In the case of achromatic colors of low luminosity a single effect in consciousness is capable of being aroused by two quite separate retinal processes, those of the rods and cones respectively. Pathological changes in the visual projection areas, however, are capable of eliminating rod vision without influencing cone vision, so that the unification of these two nerve currents probably occurs in even higher cerebral regions. It is probable that in other cases the ultimate cerebral process is more, rather than less, complex than earlier phases in the conduction.

If we follow out this line of argument the evolutionary relationships of Mrs. Franklin's visual molecule must probably be detached from the molecule and be applied to the developmental connections of the several component processes which are involved in the "color functions of the cerebrum." In this application Mrs. Franklin's evolutionary hierarchy is certainly superior to the three coördinate color pairs of the Hering theory. The development of the color perceptive apparatus has apparently been one of real evolution rather than of simple accretion. The most primitive cerebral differentiation was along the achromatic black-white dimension and this was followed, as in the Hering scheme, by a differentiation in a different dimension in terms of blue and yellow. The third step in the development, however, was not the independent appearance of a red-green differentiation but a splitting of the yellow component along these lines.

Traditional theories tempt us to identify the cerebral components above considered with individual nerve "centers." There would be a red perceiving center, a green perceiving center, etc. However, modern investigations make it probable that, at least in the case of the cerebral cortex, specific qualities of sensation depend more upon characteristic nerve *processes* than upon special anatomical centers. This does not prevent us from supposing that distinctive sensory qualities correspond with specific reflex or response tendencies. It is a well established fact of nerve physiology that certain reflex tendencies antagonize or inhibit one another, and it would appear that such a relation of mutual inhibition obtains between the cerebral components for red and green respectively. Although this antagonism results in inhibition of both "red" and "green" components the nervous energies involved are not lost but generate the "yellow" component. A similar relationship obtains between the "yellow" and "blue" components, which mutually inhibit one another but in doing so excite the "white" component. Black may be supposed to depend upon a state or process in the visual cortex which obtains in the absence of any nervous energies derived from the retina. It represents no specific reflex tendency and does not antagonize the "white" component but merely replaces or is replaced by the latter. This general schema is evidently that of the Ladd-Franklin molecule, but it is applied to the inter-relations of brain processes rather than to those of chemical constituents of a light-sensitive substance in the retina.

On the basis of the available data we can hardly hope to work out in detail the probable cerebral mechanism of color vision. All of the cerebral functions must be conceived as occurring at way stations along a line of conduction which leads from the retina to the ultimate cortical area upon which consciousness directly depends. The basic functions appear to be concerned with brightness vision, form vision, and color vision respectively. Superposed upon these are more elaborate perceptual mechanisms. Disorders in the calcarine region of the occipital cortex attack the color function most readily, affecting next in order the perception of form, while the mere recognition of brightness is the last of the fundamental visual functions to go. These facts make it likely that the chromatic function occupies one of the higher strata of the cortical mechanism. This is in harmony with the general idea that the chromatic sensibility appeared in the process of evolution after light and form sensibility had been firmly established.

If we trace the visual response arc backwards from the ultimate cortical area towards the retina the question immediately arises as to the manner in which the several components of the visual process are represented in the nerve at various neural levels. The facts of three-color mixture, and the arguments with which the Young-Helmholtz theory has made us familiar, indicate that between the ultimate cerebral region and the retina this nerve conduction must involve at least three independent variables and that three are sufficient. *A priori* there are many different ways in which we can conceive the mechanism of this triplex conduction. Helmholtz assumed that there were three different kinds of nerve fibres and receptors in the retino-neural mechanism. Some later thinkers, abandoning the three-fibre theory, have imagined a threefold qualitative differentiation of the nerve currents passing along a single nerve fibre.

Recent discoveries in nerve physiology make the latter type of explanation even more difficult than it was at an earlier date, and it has never been very plausible. Prominent among these discoveries is the demonstration of the so-called "all or none" principle for the response of nervous tissue. It appears from the researches of Adrian and Lucas that the impulse which passes along a nerve fibre is incapable of quantitative variation, being fixed in magnitude by the inherent properties of the fibre. Gradations in muscular activity under the control of motor nerves are to be explained primarily in terms of variations in the number of nerve fibres in the nerve in question which are simultaneously in action. However, a further possible basis of gradations can exist in the *frequency* of the impulses, reaching the muscle along any given fibre, since the nerve current is intermittent or pulsatory in character and the individual pulses may be densely or sparsely distributed. In the case of visual sensation it is impossible to explain gradations of intensity or luminosity on the basis of the number of fibres simultaneously in action, since the number of fibres is reserved to determine our recognition of the *area* of the retina which is stimulated. It appears to be necessary, therefore, to account for the transmission to the brain of variations in intensity of stimulation of the retina by means of the conception of nerve impulse frequency, a weak stimulus sending fewer pulses per second along the optic nerve fibres than a stronger stimulus.

Recent investigations of my own appear to demonstrate the actual operation of the "all or none" principle in the optic nerve fibres, so that it is impossible to escape from the implications of this principle for vision by supposing it to be inapplicable to sensory nerves. There is an easily demonstrable entoptic phenomenon, first described by Purkinje, which seemingly depends upon stimulation of certain retinal receptors by the nerve currents generated in the conducting fibres of the retina as a result of stimulation of other receptors. The apparent brightness of the effect produced by this secondary excitation ought to be indicative of the intensity of the retinal nerve currents, and I have found by measurements of this brightness that it is substantially independent of the intensity of the stimulus which is initially applied to the retina. In other words, the nerve currents set up in the retinal and optic nerve fibres are independent in amplitude of the intensity of the stimulus which arouses them. But these currents must have some variable characteristic which represents the intensity of the stimulus, and apparently the frequency of the component impulses is the only plausible factor which can subserve this function.

The view that the intensity variable in the optic nerve currents is the frequency of the individual nerve impulses is obviously inconsistent with the assumptions of certain visual theories which have accounted for the transmission of the qualitative or wave-length aspects of the stimulus to the brain by means of impulse frequency. These theories based on the analogy of the telephone—like the Rutherford theory of auditory response—have relied on variations in the amplitude of the nerve pulses to transmit the intensity factor. According to the "all or none" principle, variations in the amplitude are impossible. The telephone theory of visual response is moreover inadmissible for another reason which has not in general been recognized by critics of this theory. This reason lies in the relation between the extremely high frequency or small wave-length of the radiation which stimulates the retina and the very low velocity of the nerve impulse as compared with the velocity of propagation of the radiation. This relationship demands that a telephonic representation of a light wave in the nerve current should be composed of waves whose length is far smaller than the diameter of an electron. Such a demand obviously reduces the theory to an absurdity, since the only manner in which these waves could be formed would be in terms of some sort of displacement pattern of the component particles of the nerve tissue, these being thousands of times larger than the required wave-lengths.

In the second installment of this paper I shall consider in greater detail some of the problems which arise from the application of the "all or none" principle to the visual conduction process. This principle appears to provide us with a reliable postulate which can be employed in sifting various alternative conceptions with regard to the nature of the peripheral visual mechanism. The problems of the character of the optic nerve currents and of the nature of the retinal receptor process are very intimately related. Although, as previously stated, I do not hope to develop any complete solution of these problems yet I believe it is possible to arrive at certain preliminary conclusions which may form the premises of some future argument in the light of data which we do not as yet possess.

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Editorials

Two Maxims—The Golden Rule of Refraction

DR. ALEXANDER DUANE, in a recent issue of the *Archives of Ophthalmology*, closes his valuable contribution with two maxims which he believes sum up the whole matter of handling refraction cases. He says:

> "*First*, let us find out all we can about the eyes we are treating and the symptoms of which they are a part; using to this end every means that experience has proved to be helpful, never doing work in a hurry and remembering always that this work of all others requires patience, thoroughness, and accuracy.
>
> "*Second*, let us constantly bear in mind the fact that we are treating patients, not eyes; we are handling human beings, not machines; and that we cannot do our best work unless in each case we put ourselves in touch with the individual man before us, showing sympathy for his troubles, consideration for his infirmities, and an understanding mind to take in all the physical and mental factors which may affect his outlook on life and determine his need for refractive or other correction."

Dr. Duane has written the Golden Rule of Refraction—to do unto the body and the eyes of another as you would have them do unto your body and your eyes. The Great Teacher laid down the two great commandments upon which hang all the law and prophets: "Thou shalt love the Lord thy God with all they heart and with all thy soul and with all thy mind. This is the first and great commandment. And the second is like unto it: Thou shalt love thy neighbor as thyself"—the great doctrine of the true realization of the best that is in us through a service to our fellow man.

The three Graces—patience, thoroughness, and accuracy! How easy the sin that besets us all as servants of our fellow men! How hard it is to be patient, to be thorough and to be accurate! To be patient requires a soul ever permeated with a true appreciation of the work in which we are engaged and a genuine sympathy for those with whom we come in contact. To be thorough requires skill and experience and time —never doing work in a hurry. Good pieces of work are not done in a few minutes' time by an Infinite Intelligence, much less by beings limited and circumscribed in knowledge. To be accurate requires not only patience and thoroughness but also a mind well filled with fundamental knowledge and ever keen and alert to grasp the significance of the facts disclosed in the work carried out—"an understanding mind to take in all the physical and mental factors which may affect the outlook on life."

Indeed, "we are treating patients, not eyes; we are handling human beings, not machines." Would to Heaven that every person presuming in any wise to care for his brother might realize the full significance of those words and in their realization teach himself Patience, Thoroughness, and Accuracy.

The Lack of Achromatism of the Human Eye

IN any optical instrument there are two things which should be eliminated as much as possible. These are chromatic and spherical aberrations. The normal eye, while being a wonderfully adaptable instrument, is not free from errors owing to the fact that it is optically so very simple. One of the chief errors is its lack of achromatism.

If a simple lens is taken and the image of an object illuminated by a continuous spectrum-ed source is formed, the image will be found to have a red, blue or purple fringe. This is due to the difference in refractive index of the medium for rays of different wave-length. Since the refractive index is greater for rays of short wave-length, the blue rays will be deviated or bent more than the yellow rays and these in turn more than the red rays. The eye naturally focuses for the brightest rays; in ordinary light these are the yellow or yellow-green rays. Hence, the blue and red rays will be out of focus with the result that the image of a point will be surrounded by a purple fringe.

The lack of achromatism of the eye can be easily demonstrated. If we look at a spectrum in a spectroscope we find that it is impossible to have the red and the violet in focus at the same time; we are apparently myopic for the violet in comparison to the red and we shall have to adjust the eyepiece of the spectroscope by pushing it in further when viewing the violet. A normal visioned person is myopic in violet light. This experiment can be modified by producing a line spectrum on a piece of ground-glass. If viewed at the usual reading distance, the yellow and green lines may be put sharply in focus but the blue and violet lines will be hazy and quite out of focus. If the eye is brought closer these violet lines will appear clearer and if viewed from about six inches these lines will appear clean-cut. It will be found impossible to accommodate the eye sufficiently to focus the yellow and green lines.

Again, if certain test types which can be read easily at twenty feet but at no further distance be illuminated with blue-violet light it will be found that it is no longer possible to read them.

It is also quite easy to notice the same condition on viewing a spectrum (projected on a screen) from a considerable distance. When the red end is clearly visible as a rectangle the violet end appears blurred and irregular.

If a series of concentric circles, drawn in black ink and fairly close together, are viewed by reflected light and are slowly approached toward the eye or looked at steadily for a few moments at a point close to the eye, these circles will appear colored.

A purple glass is especially useful in demonstrating these phenomena. Nearly the whole of the middle of the visible spectrum is absorbed by it, the red and violet being transmitted. If a screen with a pin-hole in it is employed and the purple glass is placed behind it, we shall see that the pin-hole appears either as a red dot surrounded by a halo of violet or as a violet dot surrounded by a halo of red, according to whether we accommodate for the red or the violet. There is only one position in which the pin-hole can be seen as purple and that is when the eye is accommodated for a point midway between the red and the blue. Under these conditions the pin-hole appears larger and not so clearly defined.

The emmetropic eye appears to focus principally for the green or yellowish-green region. This can be simply illustrated in the following manner: If two sentences are printed on a black background, the letters being formed by an intermingling of red and blue dots, one sentence being in blue and one in red, an emmetrope will, on looking at these from a distance, see only a confused mass of red and blue spots. This quite clearly shows that the emmetrope focuses in general for the yellow-green rays. If the emmetropic condition be made slightly myopic by weak convex lenses, the observer will be able to read the sentence formed by the red dots. By using weak concave lenses and thereby rendering this eye hypermetropic, the sentence composed of blues will be read. In a similar manner a hyperope will read the blue letters better because the blue and violet rays, being most refracted, give the clearest images. In an uncorrected myope the reverse is true.

Emmetropization

IT is very easily possible to possess a misconception of the changes which take place in the refractive condition of an eye as it progresses from infancy to the adult stage.

The eye of the new-born child is much smaller than that of the adult, being about 17 mm. axial length instead of about 24 mm., or an inch, which is the approximate size of a normal adult eye. Since one millimeter difference in depth of an eye corresponds to about three diopters of refractive variation, it follows that the difference in the depth of a child's eye and a normal adult eye, *i.e.* seven millimeters, would correspond to an axial refraction of about twenty diopters if the young eye were built on the same refractive plan as is the adult one. As a matter of fact, the child's eye is rarely hyperopic as much as two or three diopters and often there is no error at all. Hence, there must be a combination of two factors, namely: an axial shortening sufficient to produce about 20 diopters of hyperopia and an excess of curvature or of refractive index capable of causing a myopia of about 18 to 20 diopters. We might, therefore, expect to find the curvatures of all surfaces increased in the same proportion. It might appear as though the curvature of the cornea would be considerably different, since we commonly think of the eyeball as approximately a sphere with the addition of a portion representing the cornea and hence, if the depth of the child's eye were considerably less than that of the adult eye, we might expect to find a shorter radius of corneal curvature in the young eye. This is not so. Holth, —by the clever device of injecting a solution of gelatine under the cornea as the aqueous was drained, measuring the anterior curve and then carefully removing the cornea and thus, by contact of the gelatine with the inner side of the cornea, possessing a curve exactly mating it—found that the radius of curvature of the two sides of the cornea respectively differed but little in the cases of a child 2 months old, a woman 76 years of age and a man of 44 years. Axenfeldt's results are in accord with those of Holth. The dioptric power of the cornea varies ordinarily from 42 to 48 diopters; values which are found in very young children are near to this upper limit. Compensation for the diminution in the length of an infant's eye is made by the crystalline lens.

From the researches of Stadfeldt we learn that the thickness of the crystalline lens of a new-born child is the same as that of the adult, but that the diameter is about 6 mm. instead of 8 or 9 mm.; hence it follows that the curvatures of the crystalline surfaces are greater than for an adult. Experimental results show that the posterior surface of the infant's crystalline is 4 mm. as against about 6 mm. for the adult; the most marked variation is in the anterior surface of the crystalline lens, in which case the radius of the adult lens is about 11 mm. as compared with 4.5 mm. for that of a child.

As the child's eye grows, therefore, two opposing processes are at work at the same time. The curvature conditions of the crystalline change and diminish, thus causing a reduction in the curvature myopia; while, on the other hand, the eyeball elongates, causing a reduction of the axial hyperopia. Hence the eye tends to emmetropization constantly as it grows. Without doubt, under our present so-spoken-of civilized state of affairs, the process is somewhat interfered with by conditions due to environment, such as excessive eye work and other non-hygienic uses as well as failure to care for the eye. The marvel is, therefore, not that there are so many eyes which show small imperfections but that there are not millions of eyes which are quite radically in error refractively. That the condition of emmetropization should hold so closely as it does is but an evidence of the fact that the possession of clear vision, under conditions which are the least taxing possible, has become the heritage of the human race in large part.

Retinal Asthenopia in the Industrial World

THE word *asthenopia* conveys the notion of weak, tired, and painful vision; it is generally the result of straining some portion of the mechanism of the eye. The vision itself may be normal but the act of vision, especially day in and day out under improper lighting conditions in factories, offices and homes, may produce this train of reflex symptoms known as asthenopia. We may divide asthenopia into three classes: (1) *retinal*, in which case the eyes cannot stand light without pain and there is an intolerance of light or photophobia; (2) *muscular*, in which the muscles controlling the movements of the eyes suffer from fatigue, thus causing pain and (3) *accommodative*, in which the ciliary muscle, either through refractive errors or overwork, becomes involved. Retinal asthenopia is not commonly found disassociated from accommodative and (less frequently) muscular asthenopia. For refractive errors, which throw an extra load upon the ciliary muscle and frequently upon the lateral extrinsic muscles—which load may possibly be born without any untoward symptoms under ideal conditions of lighting and chance for relaxation—are very often the superinducing cause of retinal asthenopia. Hence, in complaints of photophobia the ocular practitioner would very naturally and properly look to the removal of refractive errors through correcting lenses and the alleviation of muscular anomalies.

But it is to be remembered that the eye sees things through the effect of light falling upon a sensitive retina. If this light be over-bright or if the retina by reason of over-exposure or through disease becomes hypersensitive there ensues a disturbance of vision. The results of eyestrain are manifold and no two persons have the same *ocular capacity*. The sensitiveness to light varies widely in different individuals, both in the ability to see distinctly under faulty lighting and in the ability to work without exhaustion in strong light. There is much literature indicating that there is both *power* burn and *ultra-violet* burn and hence that both *intensity* and *quality* of light have marked effects upon the visual efficiency. Furthermore, rather insignificant but long sustained or continued light irritation may be a factor in many degenerative changes in the retina and choroid. Retinal asthenopia is, in such conditions as these, a common symptom. In such cases the use of proper ophthalmic glasses, reducing the total quantity of light or eliminating the shorter wave-lengths or accomplishing both if so desired, has resulted in great comfort.

Let us consider for a moment our natural lighting sources and lighting conditions. North light is soft and even and well diffused. Artificial light must be more concentrated and intense to give the same amount of illumination. The human eye has its diaphragm—the iris—and this has, through evolution probably, adapted itself to respond to natural light which is rich in the longer wave-lengths and also to meet the conditions ordinarily arising, in which it contracts and dilates and acts as a regulator of the light energy admitted to the eye. A sudden and extremely bright light "hurts" in all probability, not because the retina is particularly disturbed but because of the sudden and extreme contraction of the iris. Constant exposure to bright light means, therefore, a constant iridic contracture and causes fatigue. In the opinion of the writer this is the real source of the trouble in the bulk of cases; *i.e.*, it is *iridic* (sphincter) asthenopia rather than retinal *per se*. If, however, under prolonged labors the sphincter should fatigue—and this would be likely to occur in many cases—then genuine retinal asthenopia would occur because of the admittance of excessive energy to the eye. Furthermore, intense and long-continued exposure to bright light causes exhaustion of the retina. The chemical changes are then evidently about as rapid as the replenishment of the material or materials—whatever these may be—upon which light acts to give the sensation of vision, and the eye gets into a non-sensitive condition with the result that the retina is capable of responding to powerful stimulation only. Hence the eye becomes "blind" except in the strongest of lights. Therefore many workmen will demand intense light sources temporarily because the eyes have been "blunted" or "dulled".

Under such conditions the glare may do no harm but work cannot be carried on as long without fatigue. And in other persons, on the other hand, the retina does not become nonsensitive but rather hypersensitive and ultimately nearly, if not absolutely, incapable of bearing any normal exposure to light. There are certain occupations, such as those of gilders and polishers, in which the eyes of the workmen are fixed for long periods of time on bright surfaces and retinal asthenopia is thereby invited.

The arrangement of lights as well as their intensity is of importance in the prevention of retinal asthenopia. A bright light shining directly into the eyes interferes with clear vision and lights which enter the eye from below are much more annoying than those from above. Yet many machines in factories are placed so that an operator has to face a window or a bright light. Insofar as possible light should come from above, behind, and to one side. It is probably true that most of our factories are overlighted at the present time from the standpoint of the actual number of candlepowers employed in a given space for illuminating the machines and other working devices, but the distribution is in many instances sadly at fault. This is, however, fundamentally and properly a problem for the illuminating engineer.

One authority on factory lighting lays down the following four rules which are readily comprehended:

1 Sources of high intensity must not be in the field of ordinary vision.

2 The amount of light must be sufficient for the work to be done.

3 The distribution of light should be uniform or as nearly so as possible.

4 The color should be pleasing to the eye.

An adherence to these principles, which are very easily stated, involves considerable study and possible experimentation in any particular set of conditions.

Therefore, in conclusion, it may be said that retinal asthenopia is a dangerous condition particularly because of the insidious way in which it often develops. There is often a gradual reduction of eye-efficiency, ultimately interfering with the subject's labors and demanding rest and the best of care. A temporary retinal asthenopia induced by excessive localized lighting is conductive to accidents since the retina is at that time blunted and non-sensitive.

The Starting Point of the Relationship Between Convergence and Accommodation

David Kletzky, D.O.S.

THE relative aspect between convergence and accommodation is a decidedly indispensable study with which the refractionist should become thoroughly familiar, because failure might incur very unpleasant consequences in the practical application of his art. As a matter of fact, it is agreed among the best authorities that many of the obscure phenomena in the refractive apparatus, as well as of the imbalances of the extra-ocular muscles, are laid open by the understanding of the physiologically fixed relationship between these two functions.

How accommodation is affected in the eye in order that we may see clearly while looking at objects within infinity is too well known by every student, and no reiteration is necessary. Likewise is the fact well expounded that a sort of relationship exists between the function of accommodation and that of convergence. Yet it seems to me that a closer scrutiny should be given to the relationship between these two functions than it has received in the past.

Above all, it appears to me that the starting point at which this relationship between these two physiologically interdependent functions, especially as to whether their relationship begins at one and the same point, has as yet in the case of the accommodative function not been fixedly determined. It is well known that the starting point of convergence primarily begins with a divergence of the visual axes, *negative convergence*, and not with a state of parallelism. How about the function of accommodation? Is it not possible that the function of accommodation likewise begins at a point negatively situated, just as is the case with the function of convergence? We know that these two functions are guided simultaneously according to a fixed physiologic law, namely, that of one meter-angle of convergence of the visual axes to one diopter of accommodation. And, while it is true that the ratio of the one meter-angle to the one diopter of accommodation is based upon convergence, for the first—the two visual axes being primarily parallel,—and upon accommodation, for the second function—the two eyes should be also primarily in their static state; that is, adjusted to focus none but parallel rays of light. This is a premise which is without doubt correct. But, how about the meter-angle, more or less, of negative convergence each of the eyes must, of necessity, at first overcome before their visual axes are placed in parallelism?

In the face of the foregoing it appears that the innervational impulse of the negative part of convergence is in the above instance non-relative to the innervational impulse of accommodation. In other words, it leads to the assumption that, for emmetropic eyes, while the natural tendency of the two eyes is, under the suspension of the innervational impulse, toward a state of divergence, the refractive status of the two eyes, on the other hand, is in the position to properly focus parallel rays without the aid of the accommodative mechanism. To be more explicit, it means that the two eyes first of all converge from their divergent state to the position of parallelism, and that the relationship of convergence with accommodation begins at that point in emmetropic eyes.

The writer proposes to show, however, that such is not the case. And moreover, we shall presently show that the two eyes are possessed of an element which we might designate as *negative accommodation*. And furthermore we believe that this negative accommodation bears the same relationship to the negative part of the convergence as the positive part of convergence bears to the positive element of accommodation. Therefore we shall endeavor to establish the fact that the two functions, from the innervational standpoint, have for their physiologic activities one and the same starting point, and that their relationship actually begins on the negative side of the two functions in emmetropia as well as in all states of ametropia.

The reason why the writer is aiming to establish this point so effectively is because he positively holds *that the basis for comfortable, enduring and undisturbed binocular single vision is found only in an undisturbed innervational synergism of physiologically related functions of the binocular visual sense organs.* In this is included the whole category of binocular functions. Apart from the established related function of convergence and accommodation, it takes in the function of co-ordination of the eyes for parallel vision; likewise the function of moving the two eyes evenly up and of depressing them evenly downward, or the movements to the right or to the left; in fact, it refers to all movements which the eyes are physiologically capable of making throughout all of the directions of the visual field.

The term *innervational synergism of binocular movements* is not to be interchanged with *muscular* synergism, or synergistic muscular action. Synergistic muscular action simply means that a certain movement in one direction of the single eyeball is accomplished by more than one muscle. Thus, as a simple illustration, the superior rectus and the inferior oblique tend to rotate the eyeball directly upward. These two muscles are therefore synergistic muscles, because they aid each other in that particular movement of the individual eye. Likewise is this the case with the inferior rectus and the superior oblique—synergistic muscles which tend to rotate the individual eyeball directly downward.

By *innervational synergism of binocular movements* we have reference to an equally effective *innervational* influx while the two eyes make the same rotational movement. For instance, let us exemplify this in the case of a deficiency, or weakness, in the inferior rectus of the right eye. A rotational movement of the two eyes equally and directly downward would, therefore, necessitate a greater amount of innervational influx in the case of the weak inferior rectus of the right eye than would be required for the same movement by the inferior rectus of the left eye. This is what would be called a disturbed binocular innervational synergism. Such a condition, as in the case just exemplified, is usually designated as right hyperphoria. On the other hand, if the two eyeballs accomplish the act of moving equally and directly downward or upward, without some of the muscles concerned in the act showing any deficiency in their structure or in the innervation, we then have a condition of perfect innervational synergism for these particular movements, or vertical orthophoria.

The above is touched upon simply to show that the normal function of binocular vision in all of its aspects is greatly dependent upon an innervational synergism of the highest order. Hence, our reason for attempting to prove through that which is to follow that accommodation, like convergence, has a negative aspect and that the two functions possess a common synergistic innervational starting point.

The so-called emmetropic but living eyeball cannot be compared to the mechanically contrived schematic eye. Nor is it to be considered in the same light as we find it represented in the faultlessly drawn diagrammatic delineations of the text book, with all the technically accurate tracings of imaginary ray-formations and transformations. Nature is not so kindly disposed in this particular instance, because ametropia most assuredly is the rule and not the exception.

However, when we consider the very important factors which chiefly contribute toward the proper sense interpretation of clearly defined distant visual impressions, namely: that parallel rays of light impinge in the most exact incidence on the fovea which is essentially devoted to direct vision, and also that focusing of such high character must of necessity be dependent upon an unchanging and very firm construction of all the component parts (the eyeball and refractive media), we can hardly imagine that the living elastic eyeball with its even more elastic media could, by any means other than by the aid of innervational and muscular effort, perform this function in a manner so precise and so regular.

Therefore, if we are to assume the position that, in the so-called emmetropic eye, accommodative muscular effort is a physiologic necessity in order to at first tune up, so to speak, the refractive components of the eyeball before any kind of rays, parallel or otherwise, are properly focused upon the fovea, then the problem hinges upon the proposition thus: whether this accommodative effort is relatively likewise associated negatively, and, as we hold to be the case in binocular fixation, synergistically, with the negative starting point of convergence.

We know that the eyes, under normal conditions, have in them an element properly designated as negative convergence in an amount, more or less, very close to one meter-angle. In that case, if we are to expect the existence of a negatively situated innervational synergistic binocular function of convergence and accommodation, then, the negative element of accommodation must likewise obtain in such an amount that the fixed ratio of one meter-angle of convergence to one diopter of accommodation remains unbroken. And, as the negative part of convergence, under normal conditions, runs in the proximity of from three-fourths of a meter-angle up to one and one-fourth, for each eye, we can therefore readily see that under normal conditions, likewise, the negative element of accommodation for each eye would have to equal that of the negative part of convergence if the eyes are to maintain the binocular innervational synergism which we claim is so necessary for undisturbed comfortable vision for all distances of the gaze.

Certainly, a tonic contraction on the part of both ciliary muscles in order to increase the curvature of the crystalline lenses in the small amount, say, from three-fourths to one and one-fourth diopter is not, after all, such a great im-probability, if we consider the fact that the ciliary muscles, apparently more so than any other muscles, as investigations tend to show, are exceptionally inclined to be very rigorous in their tonicity. Obviously, this rigorousness is effectually kept up because the ever-present instinctive impulse for clearly defined visual impressions intensely commands this extra tonicity in ciliary contraction. This instinctive impulse for clear vision is quite often so forcible that, for some cause or other, it apparently overdoes things,—that is, it induces spasm of accommodation resulting at times in pseudomyopia of low degree.

Aside from what is stated above in reference to the possibility that the emmetropic eye possesses an actively negative accommodative function, and that this function is primarily inherent in the eye for the purposes of (1), acting relatively and synergistically with the negative function of convergence, and (2), establishing a sort of fixed and firm condition in the crystalline lens in order that focusing may take place upon the fovea in the nicest possible degree, we can still find other evidence that the eye possesses a negative element of accommodation.

Let us, for instance, first consider the attendant removal of supplementary lenticular strengths, which is the usual sequence following paralysis of accommodation, either induced as the result of instilling a cycloplegic drug into the eye, or, as the sequence of post-diphtheritic, toxic, or syphilitic affections, *et al.* That such paralysis augments a previously existing hyperopia is well known. Likewise is the fact pretty well established that such paralysis *decreases* a previously existing myopia, or, as is the case also, it frequently induces a hyperopia in an eye which had long been known to possess perfect emmetropic vision. Also the fact is well known that the reduced lenticular strength within the eye, caused by the paralysis of accommodation, can be corrected artificially by lenses of one kind of dioptric strength while the eye is under the effect of paralysis, and by lenses of a different kind of dioptric strength when the eye recovers from the effect of the paralysis.

In my practice I have observed, and I presume a great many readers have likewise observed, that quite a number of patients who have been known to use, for many years, myopic lens corrections of unchanged strength with perfectly normal distant vision, fitted, as they were, with the utmost accuracy; nevertheless, an acute paralysis of the accommodation of one or both eyes, from some cause or other, necessitated a reduction in the strength of the spherical element of their minus lenses during the period the paralysis was in existence.

Of course, in such paralysis of accommodation in hyperopic eyes the previously used lens corrections would have to be increased in dioptric strength. But hyperopia, some would say, tends mostly toward latency; hence we shall leave hyperopia out of the question. How about myopia? The myopic eye most assuredly ought to be the very eye in which not even the slightest vestige of ciliary accommodative concealment should reveal itself as the result of such paralysis. Yet, apparently, this primary accommodative tonicity is there also. This, of course, leads to the positive conclusion that it is a negative accommodative function inherent in all eyes irrespective of the refractive status and, therefore, seemingly has its relative and necessary position, in its negative aspect,—in the way of establishing proper focusing of images coming from objects situated at infinity—with the normally negative part of convergence which is, likewise, a most necessary state in the manner of affecting a certain amount of tonicity in the internal recti in order to bring about perfect and fixed parallelism of the visual axes for infinite binocular fixation.

It is to be understood, however, that just as we cannot, at will, diverge our eyes and thus relax the tonic contraction of the internal recti (the negative part of convergence), while the look is directed at infinity, so also are we unable to relax, at will, the negative element of accommodation while looking at objects situated at infinity. Particularly is this the case where the refraction is naturally emmetropic or made so artificially with lenses.

The fact that accommodation, unlike convergence, diminishes in amplitude physiologically with the advancing age of an individual and that therefore its relationship with that of convergence gradually comes to an end on the positive side of both functions (and in the very old, negatively; that is, acquired hyperopia of the aged), is not, in a physiologic sense, an element of much concern. The main import centers in their relative starting points and not in the way the two functions end.

In other words, if a pair of emmetropic eyes is possessed of only, let us say, one diopter of amplitude of accommodation, then the innervational impulse necessary in order to supplement a lenticular strength in the amount of this one diopter must start synergistically with the primary innervational impulse of convergence, irrespective of the fact that the function of convergence is able to keep on converging the eyes at a nearer distance than the eyes can accommodate. This ending of their relationship on the positive side of the two functions is corrigible, in the case of the accommodation function, through plus lenses and thus the relationship of the two functions is again artificially re-established. Likewise is this the case when the accommodative function exceeds in amplitude that of convergence; *i.e.*, their relationship is marred because of convergence being weak or insufficient. Here again we are enabled to re-establish their normal relationship artificially by the aid of prisms or by decentration of the optical centers of lens corrections.

The writer has simply touched upon the possible existence of a negative element of accommodation in order to prove his contention in the premises, namely: *that convergence and accommodation have a common negative starting point*, *and that* *the innervational impulse of both functions is binocularly synergistical under normal conditions.*

From the above standpoint we can elucidate a great many phenomena which obtain in connection with the toleration and non-toleration of certain lens corrections.

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Ophthalmometry and Its Applications to Ocular Refraction and Eye Examinations

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THE ophthalmometer is, without doubt, a much abused and consequently a much disused instrument. It is probably true that a discussion of ophthalmometers and ophthalmometry in a group of men interested in refraction would evoke very decided expressions of opinion both favorable and unfavorable to its usefulness. Be that as it may, we are of the opinion that the ophthalmometer is one of the most valuable instruments that we have in refractive work and we hope to defend our position in the succeeding paragraphs. Incidentally, let it be stated at once that the findings by ophthalmometry and the ultimate prescription given the patient, in so far as the astigmatic correction is concerned, may not be in agreement. There are various reasons why this may occur. Furthermore, differences in various sets of findings by different methods (*e.g.* ophthalmometry, retinoscopy—both static and dynamic—and subjective tests—both with and without cycloplegics) should lead to a careful, analytical study of the case in hand from all standpoints. Variations in data by different methods ought always to furnish us with the information needed for the final analysis of the case and the expression of our judgment as to the corrections to be offered or the treatment to be accorded. Let us, then, briefly state the following facts germane to the topic under discussion: (1) The ophthalmometer measures anterior corneal curvatures and astigmatic conditions only; hence these findings may be ultimately modified by posterior corneal conditions or by lenticular conditions involving regular or irregular astigmatism. (2) The subjective findings and corrections are obtained with lenses inserted somewhere near the region of the anterior focus of the eye: the effectivity of all lenticular corrections varies with the distances from the eye at which they are placed: hence ophthalmometric findings, on the one hand, and subjective and retinoscopic data on the other hand, may not apparently agree, whereas they may be in very good accord when proper allowance is made for the conditions which have just been cited. (3) The ophthalmometer does accurately measure the curvatures in various meridians of the anterior corneal portion of the eyeball, hence affords some evidence as to whether or not the myopia or hyperopia subsequently disclosed by other tests is due, possibly, to axial or refractive conditions. (4) It furnishes a ready means of discovering irregularities of the cornea, which cause irregular astigmatism and generally produce reductions in the visual acuities.

The Ophthalmometer

The first instrument was devised by von Helmholtz, who published a description in 1854. In the 80's Javal and Schiötz improved the instrument and gave it a semblance of the form it has today. Thus far ophthalmometers measuring corneal curvatures only have been perfected. Claims have been made as to the invention of instruments measuring lenticular conditions, but none have, to our knowledge, been sufficiently perfected to warrant their general use in office practice. It is obvious that if the prisms in the telescope of the ophthalmometer are made movable, so that they can be shoved to and from the eye, we should have a scheme which, theoretically at least, should enable us to examine the cornea and the anterior and posterior surfaces of the lens. Special mires would be needed in order to give sufficient illumination and clarity of images. Such an instrument ought, if perfected, to aid in the settlement of many points of scientific interest; such, for example, as the mechanism of accommodation, the question of accommodative astigmatism, *et al.*

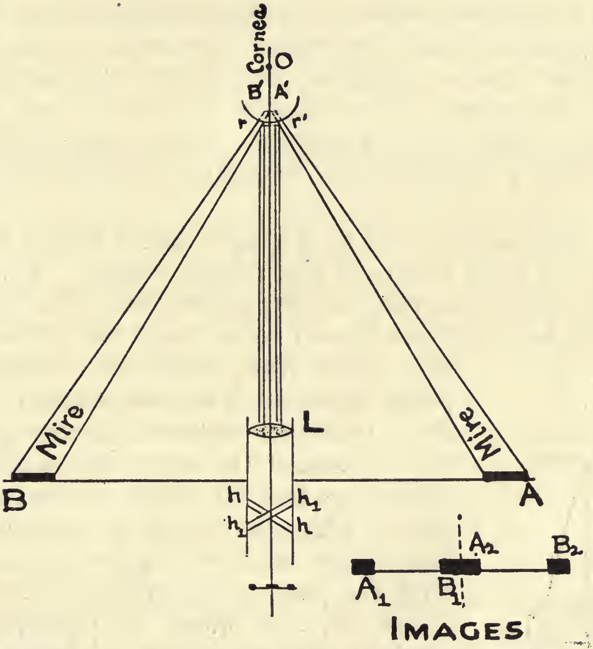

Figure 1. Diagram illustrating the essential physical principles underlying the construction and use of the ophthalmometer. The four images as produced by the doubling device are shown in an enlarged form at the lower right-hand corner.

The fundamental parts of the ophthalmometer are the *telescope*, which carries the objective and an eye lens, a double refracting *prism* and a set of *mires*. In some instruments the overlapping or separation of images of the mires as seen through the telescope is controlled by a movement of the mires through the rotation of a worm device whereby the mires are moved along an arc; in another type of instrument the mires are stationary but the positions of the reflected images of the mires, as seen by the operator, are varied by changes in the position of the prisms. These prisms are fitted into a special tube and carried back and forth by a rack and pinion device. In certain instruments the so-called "primary" and "secondary" positions can be readily turned from one to the other respectively by a simple rotation of the prisms. One form of instrument, not as successfully developed as we judge it can and ought to be, gives both primary and secondary findings in the field simultaneously.

The *birefracting prism* is of quartz and is so cut with respect to its optic axes as to give double images. This prism is, in reality, composed of two prisms with the apices in opposite directions, so placed as to cause the deviation to take place from each side. Since each prism produces a certain degree of deviation, twice the amount of separation is secured and at the same time the doubled images can be kept nearer the center of the field. The prisms are so mounted that their plane of doubling is in exact line with the plane of the graduated arc.

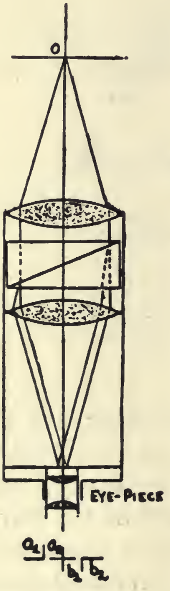

Figure 2. Detailed diagram of the objective, prism system, and ocular of the telescope of the ophthalmometer.

The *telescope* should be equipped with combinations of achromatic lenses. This is, in general, approximately the case, but we find in practice that the reflected images of the mires as seen in the field of vision under the magnification of the ocular of the telescope are often accompanied with colored fringes and indistinct edges which interfere with the determination of the exact coincidence of the mires in corneal examinations. These slight color fringes are due, without doubt, to *diffraction* effects which are produced by the texture of the cornea and which may, for example, cause the general character of the light reflected from the cornea as seen in the telescope to be bluish or reddish; they may, as their second source, be due to the *dispersive effects* of the prism system producing the doubled images; or, again, to lack of complete achromatism of the telescopic lens systems.

This clearness and sharpness of the edges of the mires and the freedom from colored edges in the region of contact of reflected images may be acquired, so E. LeRoy Ryer says, through the use of a red screen over one mire and a green screen over the other mire, these screens having as nearly as possible complementary colors. It is desirable, however, to have access to white mires under other circumstances; hence both purposes may be accomplished by obtaining red and green colored celluloid pieces which may be slipped in between the glass plates of the mires and the mires proper. These may be inserted or removed in a moment's time. The writer has tried this scheme and found that it is excellent in some cases. For his own part, however, he has to state that, with oppositely colored mires, the phenomenon of different foci for different colors (*i. e.*, stereoscopic vision for colors) occurs, so that the mire with the red screen is not sharply seen when the green one is. But the region of overlapping and that of "just in contact" are generally sharply defined. The effects due to a set of white mires and a set consisting of a red and a green one may be simultaneously obtained and the contrast noted by inserting the colored celluloid strips in such a way as to cover only half of each mire respectively. We note, in passing, that one of the American companies manufacturing ophthalmometers has for some years stated in its descriptive literature that the mires may be of any color desired, one red and the other green and so on, or both may be of white. It is their recommendation, however, that the mires be white as a general rule.

Some Practical Points in the Manipulation and Use of the Ophthalmometer

From the conversations we have had with many practitioners and from the questions asked or criticisms raised, we judge that many men do not thoroughly understand the niceties of manipulation of an ophthalmometer. Hence it is desirable that attention be called to these points.

1 The eye-piece. The examiner should first of all adjust the telescope by looking through it and turning the eye-piece (the end nearest the eye) until the cross-hairs are in perfect focus. This differs for individual operators, hence the reason for the adjustment. Likewise, these cross-hairs are easily gotten out of focus in the course of the use of the instrument. If these cross-hairs are not in proper focus, the images reflected from the cornea cannot be brought into correct focus, hence cannot be made as clearly and sharply defined as they should be. This adjustment of the eye-piece of the telescope is a frequent omission on the part of many practitioners. It should be stated, in passing, that some makes of instruments do not have such a device; this adjustment would not then be called for.

2 The patient should be comfortably seated and the instrument placed upon an adjustable table or stand in order that a comfortable and uncramped position of the head and body of the patient may be assumed. Also, the operator should give some heed to his own comfort and efficiency in his work.

3 The forehead of the patient should be pressed against the top of the head-piece and, when in readiness for observations, the patient should be instructed to keep the head immobile.

4 The patient should be instructed to look at the end of the telescope. If necessary a small white fixation object may be provided and attached very close to the mouth of the telescope.

5 The line of sight of the eye and telescope may be approximated initially by observing the relative heights of the eye and telescopic tube through the slits or apertures provided in the metal screen to which is attached the arc carrying the mires, and a little above or to the side of the telescope. Very little further adjustment should be called for in this respect since the images from the cornea should be readily obtained and seen by the observer upon swinging the telescope around in line with the eye under test and by adjusting the telescope back and forth on the rack and pinion device provided for the purpose of focusing the images of the mires.

6 The images of the mires reflected from the cornea are to be focused so that they are the clearest and sharpest possible by a movement of the telescope only, without touching the eye-piece if such is present and in adjustment. Because of backlash it is advisable to always finally focus, whether in the primary or secondary positions, from the same direction; *i.e.*, always finally focusing from a movement of the telescope forward or vice versa. This point should always be heeded when comparing the results or data on the same cornea obtained by different makes and styles of instrument.

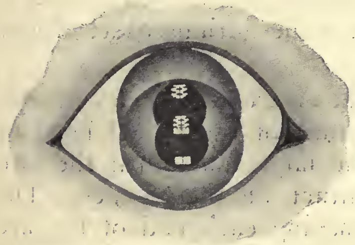

Figure 3. The corneal reflections as obtained with one form of modern ophthalmometer.

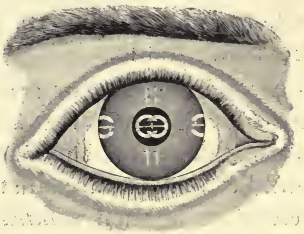

Figure 4. The corneal reflections as obtained with another type of modern ophthalmometer.

7 The patient's head should be in such a position that the eyes are *horizontal*, because if the head were tilted and

one eye were higher than the other, the apparent location of the principal meridians would not be true, but might be off as much as ten to fifteen degrees from their correct positions. This requirement is readily fulfilled as follows: After having focused upon one eye and so arranged affairs that the two inner reflections from the right eye, for example, are practically centered with respect to the intersection of the cross-hairs, then immediately swing across to the left eye and if the head is in good adjustment from the standpoint just mentioned a similar condition will exist with respect to the location of the two inner images reflected from this eye with respect to the cross-hairs. In this manipulation the eye-cover should be swung to the median position so that both eyes may be kept uncovered.

8 The corneal reflections of the two mires are doubled by the bi-refringent prisms, and of the four images seen in the field the two inner ones only (which should ordinarily, with the dial pointer set at about the 45 diopter point, be close together or possibly overlap) being regarded. These images are then made to fall upon the point of intersection of the cross-hairs in the eye-piece by a manipulation of the telescope through a movement of the same up or down and by swinging it upon its vertical axis. When this adjustment is obtained the telescope should be clamped so that it will not move from its position while various observations are being made.

9 The *mires*, (or *prisms* in the case of stationary mires), are moved along the arc by means of the milled head or worm-device on the back of the large dial, until the two middle images are just in contact at their edges. The telescope is then *rotated*, by grasping each end of the arc carrying the mires and turning with a circular motion, until the bisecting lines through each of the mires form a continuous line and the positions of the mires on the arc are readjusted, if necessary, for contact. This locates for us *one principal meridian*. (It is absolutely useless and

valueless to employ the terms *primary* and *secondary meridians* in the sense in which they are often used; all the two words connotate is *first* and *second positions of alignment.*)

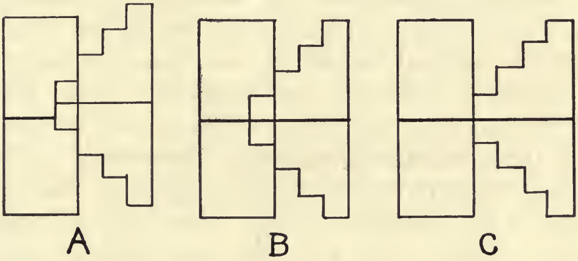

Figure 5. Corneal reflections of the mires. (A) Images overlapping and off a principal meridian. (B) Images overlapping but in a principal meridian. (C) Images in alignment and in contact in the horizontal meridian.

10 If the cornea is spherical, the central images will remain in contact as the arc, which carries the mires, is rotated about the horizontal line or axis of the telescope. If there is *corneal astigmatism*, the distance between the images will vary as the arc is rotated into various meridians on account of the variation of curvature or the *toric form* of an astigmatic surface. Furthermore, the images will have a curious excentric sliding motion with respect to each other. The two principal meridians should, under normal conditions, be 90 degrees apart. To locate a principal meridian, therefore, we have only to locate that direction in which the black central lines, or their equivalents, on the mires are continuous with each other as viewed through the telescope, since this occurs *only when the meridian parallel to the plane of the mires is spherical.*.

11 Various instructions are given with different makes of instruments as to the method of setting the pointers attached to the dial or the manipulations of the drum or dial arrangements for the adjustment of the prisms necessary

for contact of the mires in different meridians and, through them, the determinations of the corneal astigmatic error if such exists. The writer recommends, for one or two reasons which will be considered directly, that the *power in each principal meridian and the meridian measured* be recorded for each eye. Thus, if the mires are in the horizontal (0-180 degree) meridian, we measure the *power* in that meridian. This is mathematically and physically equal to the power of a cylinder of like power to that determined by the ophthalmometer with the axis of the cylinder representing this power at right angles to the meridian measured. For instance, if the mires are in contact in the 90th meridian, (*i.e.*, with the central lines continuous in the vertical direction) we are measuring the corneal power in the vertical meridian; let us assume this to be 45 diopters. We should, therefore, make our record as showing the equivalent corneal power of the eye in the 90th meridian as 45 D. cyl. ax. 180. In practice, therefore, we simply record both the *power* and the *meridian measured* somewhat as illustrated in the following:

Ophthalmometric Data

Eye	Power	Meridian Measured
Right	45 D.	90
	48 D.	180
Left	43 D.	100
	42 D.	10

These data may be conveniently recorded, as shown in the accompanying diagram, by the use of a circle and a cross drawn in the position of the principal meridians, each meridian measured being marked with the value of the power possessed.

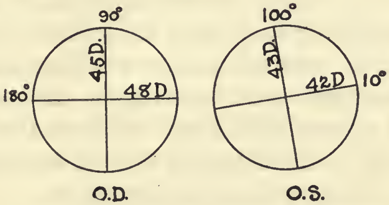

Figure 6. Diagram illustrative of a simple method of recording the principal meridians and their powers in a pair of eyes.

In the case of the right eye we have recorded an assumed corneal astigmatism of 3 diopters. There is no direct evidence, *per se*, that a minus or plus cylindrical correction will be required in the prescription, since that phase of the data must rest upon whether or not the eye has simple hyperopic astigmatism, simple myopic astigmatism or compound or mixed astigmatism. Such data must come from retinoscopic and subjective tests. Neither, again, have we any reason to believe that the ophthalmometrically determined astigmatism will agree in amount or exact axis with that finally fixed upon and judged to be the correct astigmatic finding. We shall discuss this matter thoroughly in other paragraphs. However, we do have a condition of corneal astigmatism against the rule, as it is known, since the vertical meridian has less power than the horizontal meridian. The difference in corneal curvatures in the illustration chosen is represented by the equivalent of a 3 D. cyl. ax. 180 placed in contact with the cornea. This would add three diopters of power to the vertical meridian and hence make both powers equal to 48 diopters. Or again, a −3 D. cyl. ax. 90 might be thought of as being in contact with the cornea; this would take away three diopters of power from the horizontal meridian and hence make both powers equal to 45 diopters. This would mean, in other words, that we would have made through the addition of the cylinder a spherical refracting surface of the cornea. If there were no other sources of astigmatic error in this eye, which would either add to or subtract from the total corneal astigmatism, and if account need not be taken of the effectivities of lenses at appreciable distances from the eye, we should expect to find by retinoscopic methods an amount of astigmatism approximating that just specified.

In the case of the data given with reference to the left eye, however, we have a corneal astigmatism with the rule, in which the vertical meridianal power is greater than the horizontal, thereby demanding in the illustration chosen a one diopter cylinder to make both meridians of equal power. This may be accomplished, (from the standpoint of the ophthalmometric findings but not, it is to be remembered, necessarily in exact agreement with the amount of astigmatism determined by other methods) by either a 1 D. cyl. ax. 100, which would add power to the horizontal meridian and therefore make both meridians of 43 D. power or by the use of a −1 D. cyl. ax. 10, which would take away power from the vertical meridian and cause both meridians to have equal powers of 42 D.

We shall have occasion to discuss some very vital points with respect to the significance of these corneal findings in paragraphs devoted to a discussion of theoretical and practical interpretations of ophthalmometric findings.

In closing these remarks on the manipulation and use of the ophthalmometer we desire to say that we have referred to the classic form of instrument with movable mires. Another excellent make of instrument has stationary mires with the adjustment of images made through an arrangement controlling the prisms. In the statements we have made it is, therefore, necessary to speak only of the fact that adjustment of images by the prism movement device is synonymous with movements of the mires along the arc.

Some Simple Theoretical Considerations

For all practical purposes the anterior surface of the normal cornea may be considered as a convex mirror. We know that the sizes of the images reflected in plane mirrors are of the same dimensions as those of the objects. With convex mirrors the image is always apparently behind the mirror and much smaller than the object. The smaller the radius of curvature or the greater the curvature of the convex surface the smaller will be the size of the image. Hence, if the convex mirror should be more curved in one meridian than in another, the reflection of a circular object would no longer be round but would be oval, with the longer axis parallel to the meridian of least curvature.

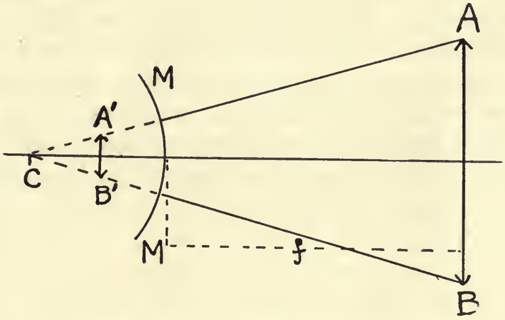

Figure 7. Illustrating the fundamental physical principles of reflection from convex mirrors or from the cornea.

The accompanying diagram shows the fundamental principles of the reflection of images by convex mirrors or the convex cornea. *M M* represents the cornea and *A B* is to be considered as a single mire. The distance *M A* is large (say a foot) as compared with the radius of curvature of the cornea which is, on the average, about 7.8 millimeters. The image of *A B*, *i.e.* *A′ B′*, will be formed back of the mirror and practically at its focal point, F = r/2.

The simple ophthalmometric formula is

$$r = \frac{2\,f\,I}{O}$$

in which r is the radius of curvature, f is the object distance, O the size of the object and I the size of the image.

This is the equation which must be satisfied in the construction of the ophthalmometer and from which it may be calculated (see Sheard's *Physiological Optics*, pages 51-53) that the strength of the doubling prism used in modern ophthalmometers is so arranged as to give a displacement of exactly 3 millimeters.

The ophthalmometer is used to find *the anterior focal power of the cornea.* The dial or disc is usually marked in both diopters and in millimeters radius of curvature. So many errors have been seen by the writer in printed statements having to do with the calculations of these dioptral powers and radii that he may be pardoned a brief reference to the correct equation and its use. The *anterior corneal focal power* is represented by

$$D_C = \frac{1000\,(n-1)}{r}$$

where r is the radius of curvature in millimeters and n the index of the cornea. It is quite commonly stated that the index of the cornea is the same as that of the aqueous or water, namely 1.333. Such is not true, for the cornea has an index commonly assigned as 1.3375. If this number is used in the above relation we find that a radius of 7.5 mms. corresponds to a power of 45D. To anyone who will take the trouble to check out the accuracy of the markings in diopters power and in millimeters radius of curvature by the foregoing equation the following may be of service:—

Power in diopters	40	41	42	43	44	45	46	47	48	49
Radius in millimeters	8.44	8.23	8.04	7.85	7.67	7.50	7.34	7.18	7.03	6.89

The Artificial Glass Cornea and its Use with the Ophthalmometer

Some makes of ophthalmometers are provided by the manufacturer with artificial glass corneas. The writer believes that a great many practitioners would gain familiarity with the principles of ophthalmometry and avoid many of the erroneous conclusions with respect to the instrument and the service it may render if they would procure one of these corneas and make a careful study of various astigmatic conditions which can thus be arbitrarily produced and which will be briefly discussed in the succeeding paragraphs. The same remark might be made with respect to retinoscopy: for a mastery of the principles of practical retinoscopy through the use of a good schematic eye costing a few dollars will ultimately lead to success when this most valuable objective method is made use of in ocular refraction.

A standard reflecting spherical surface may be inserted as a small button in the swinging eye-shield of the ophthalmometer and so situated that it will lie approximately in the plane occupied by the human eye when the head is properly fitted to the chin and head rests. This artificial cornea has a power of 45D.; this amount represents the average power of the cornea. This glass cornea may be used to test the accuracy of adjustment of the instrument, since with the dial or mires set at the 45D. point there should be perfect contact of the mires as the telescope is rotated if the instrument is in perfect working order. Furthermore, this artificial cornea may be used with cylindrical lenses from the trial case to produce various conditions of artificial astigmatism. Several points are to be noted in this connection, since the amount of astigmatism determined by the use of the combined artificial cornea and the selected cylinder will *not agree with the astigmatism apparently created by virtue of the amount of cylindrical element added.* The writer has talked with or received communications from many practitioners who believed that their ophthalmometers were either in mal-adjustment or else absolutely inaccurate because of this difference between the amount of the astigmatism as determined by the instrument and the cylindrical element artificially producing it. If, then, a convex cylinder is placed with its curved surface in contact with the sphere there is a reduction of the negative reflecting power across the axis, while a concave cylindrical lens similarly placed increases it. If R represents the reflecting power of the sphere, D the refracting power and P the power of the cylinder, it is possible to show that the following relation between these quantities holds:—

$$\text{Astigmatism} = \frac{2\,P \cdot D}{R}$$

In the case of the artificial cornea, if $D = 45$ diopters and $n = 1.5$; then, since theoretically

$$D = \frac{1000\,(n-1)}{r\ (\text{mms.})}$$

we find that $r = 11$ mms. approximately. The reflecting power of the standard cornea is, therefore, 1000/radius = 1000/5.5 or 180 D. approximately.

Hence the

$$\text{Astigmatism} = \frac{2 \times 45 \times P}{180} = P/2 \text{ approximately.}$$

That is, *the astigmatism is approximately one-half of the cylindrical power producing it.* Furthermore, the lens and the cornea will not occupy the same focal plane, hence this will cause a difference in the readings of the instrument.

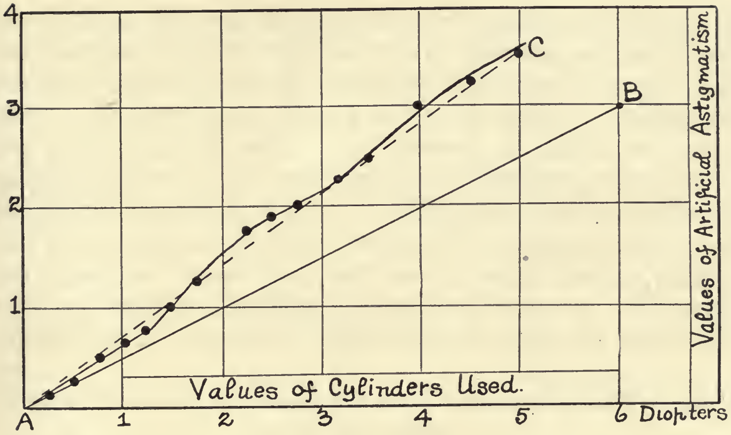

Figure 8. Curves showing the following: *A B* is the calculated relation between cylinders used and the astigmatism produced; *A C* gives the actual experimental results obtained.

Experimentation shows that the results with the artificial cornea approximate one-half of the value of the cylindrical element employed when this is about 1.5 D. or less, but that the ratio between the astigmatism as determined with the ophthalmometer and the value of the cylinder used increases and approximates 0.66 for higher powers. The following table, taken from Gibbons (*The Eye, Its Refraction and Diseases*, Vol. 1, page 386) gives a fair set of data on this point. These values are plotted in the accompanying curve.

Dioptric Power of Cylindrical Lens	.25	.50	.75	1.00	1.25	1.50	1.75	2.00	2.25
Result with Artificial Cornea	.12	.25	.50	.62	.75	1.00	1.25	1.50	1.75
Dioptric Power of Cylindrical Lens	2.50	2.75	3.00	3.50	4.00	4.50	5.00	5.50	6.00
Result with Artificial Cornea	1.75	2.00	2.00	2.50	3.00	3.25	3.50	4.00	4.50

Furthermore, it should be remembered that the addition of plus cylinders produces an artificial hyperopic astigmatism while concave cylinders produce a corresponding myopic astigmatism. Three practical points need emphasis in the use of the artificial cornea: (1) The distance from the mires to the standard reflecting sphere may be neglected as not affecting the calculations. (2) The curved surface of the cylinder should be in contact with the cornea. (3) The ophthalmometer should not be re-focussed between the first and second positions even though the thickness of the glass along the axis causes a slight blurriness in the image.

Results of the Measurements on the Human Cornea as Obtained by Ophthalmometry

Only a very small part of the cornea is used for measurement in ophthalmometry. Also, the portion upon which measurements are made is at or near the visual line, since the patient is ordinarily directed to look into the telescopic opening, unless measurements on the peripheral parts of the cornea are desired for any reason. As a matter of fact it can be shown that the images of the mires are formed by reflection from two small areas of the cornea about 1.4 mm. from the visual line. It should, therefore, be borne in mind that the normal cornea is neither a spherical surface nor an elliptical or hyperbolic curve. The best researches indicate that the central portion of the normal cornea, which is chiefly operative in vision, is approximately a sphere and that the peripheral portions are considerably flattened and decrease rapidly in power. Hence, for refractive purposes, the eye should always be directed at the end of the telescopic tube of the ophthalmometer, since the reflections from the peripheral portions will be distorted and give inaccurate results and hence are not desired.

The radii of curvature of the cornea at the summit may vary between 7 and 8.5 millimeters. Cases of keratoconus exceed this limit. Tscherning and Bourgeois measured a

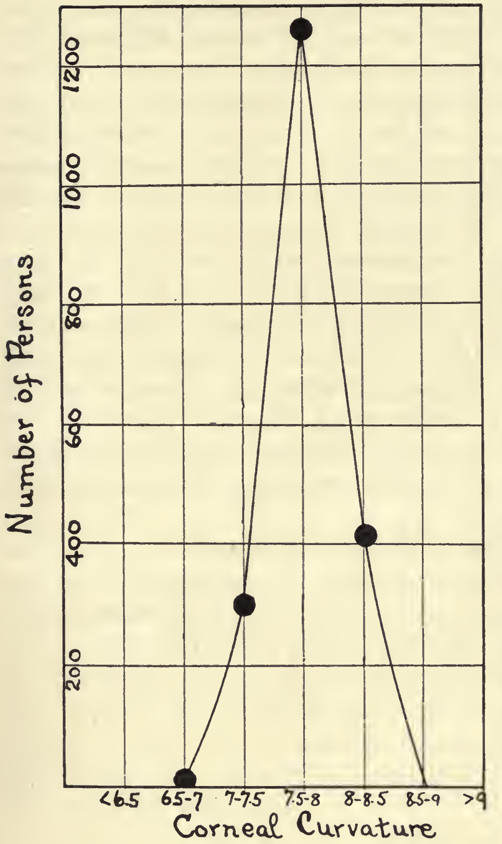

Figure 9. Diagram showing the relation between the number of persons examined and the corneal curvatures possessed. (Plotted from data by Jackson.)

considerable number of emmetropes and found a majority having a radius of curvature approximating 7.8 mms. It seems probable that 7.5 mms. is a better number, hence it may be considered that, all other factors being normal, the expectancy would be that the cornea of the emmetropic eye should possess a radius of curvature of about 7.5 mms. and a dioptric power of 45D. However, it would be an error to presume that one radius rather than another corresponds to emmetropic conditions, or to what we may call normal or standard conditions. Tscherning says with propriety that "in emmetropic eyes there exists a constant relation between the radius of curvature of the cornea and the length of the ocular axis, so that the ocular shells of different emmetropic eyes would always be a reproduction of the same type, a little enlarged or a little diminished". It is still an open question whether there exists any relationship between myopia and hyperopia and the corneal curvatures, although Sulzer, in 1896, presented some evidence that there is. In cases of high hyperopia which approach microphthalmia and possibly in high myopia there doubtless is such a relationship. Even in cases of anisometropia of fair degree, excepting cases of astigmatism, there is generally less than a half to one diopter of difference in the corneal refraction of the eyes.

We have stated that the average curvature of the anterior surface of the human cornea is about 7.5 to 7.65 mm. Amongst the latest researches on this topic are the experimental results of Edward Jackson (*Ophthalmology*, Vol. XII). He gives the following table, the results of which are plotted in the accompanying diagram in which the abscissas represent the various radii of curvature and the ordinates the number of persons possessing these curvatures.

Corneal Radii of Curvature of 2000 Eyes

Radius of Curvature	Number of Eyes
Under 6.5 mms	6
6.5 to 7 mms	10
7 to 7.5 mms	305
7.5 to 8 mms	1263
8.0 to 8.5 mms	409
8.5 to 9 mms	2
Over 9 mms	5

Possible Value of Ophthalmometric Curvatures in Hyperopia and Myopia

It is probable that the ophthalmometric measurements of curvature do lend information of value in many cases of hyperopia and myopia. Calculations show that an increase or decrease of one millimeter in the length of an eyeball along the axis corresponds to two and one-half to three diopters of refractive change. It is probable that variations in the lengths of eyes through the ocular axes are greater than are the variations in corneal curvatures. But variations in the curvature of the cornea affect the refraction to a greater extent than do variations in length. For a variation of one millimeter in the anterior corneal radius of curvature corresponds to about six diopters. Hence, high or low corneal curvatures may be important etiological factors in myopia or hyperopia or in tendencies thereto. If, then, the eye is, for example, highly hyperopic (let us say 6D.) and the corneal measurements should indicate curvatures as low as 40 to 41 diopters we should be justified, we believe, in concluding that the hyperopia was of a curvature type rather than being axial or possibly lenticular in nature. The possibilities for vision, when corrected, might be expected, other features not proving the same to be impossible, to be raised to something approximating the normal standard. But if an amblyopic eye, of 6 diopters for example, were under examination and the curvatures of the cornea were about normal and of practically the same values as those of the other eye, we should be compelled to look elsewhere for the seat of the hyperopia and of the amblyopia. The values of the visual acuity, before and after correction, would then depend largely upon the history of the case and the previous treatment.

In myopia there are two important points which should be settled: the measurement of the radius of curvature of the cornea and the examination of the fundus. Let us say that the average curvature of the cornea is 7.65 mm. as a very fair estimate. If the radius of curvature is less than this, it indicates a cornea with a sharper curvature and hence greater refractive power; whereas, if the radius be longer the cornea is flatter and less powerful refractively. In general, then, a short radius of curvature in myopia indicates that the case is of a benign refractive character in which the rays are brought to a focus in front of the retina by virtue of the excessive refractive power of the cornea. If, however, a reasonable amount of myopia exists (*i.e.* two diopters or more) and the radius of the cornea is large or even normal, there is then a fair indicator that the myopia present must be due to the displacement of the retinal tissues backward. This would indicate the progressive axial type of myopia. The examination of the fundus by means of the ophthalmoscope is of considerable value here. For, if there are no changes present in the fundus of a person with a short corneal radius it is perfectly safe to say that the case is a non-progressive one. The absence of fundus changes is not so conclusive, however, in flat corneas, since the myopia is evidently axial and not refractive and changes are likely to develop later. If, perchance, those changes are present which indicate an inflammatory softening of the structures at the posterior pole, then the diagnosis of progressive myopia can be made with considerable certainty.

Case No. 1. A hyperope, 54 years of age, requiring O.U. +7.00 D.S. ⬭ + 2.50 cyl. ax. 90, and thereby acquiring a visual acuity of 20/24, possessed the following corneal curvatures:

Eye	*Power*	*Meridian*
Right	38.0 D.	180
	40.5 D.	90
Left	38.5 D.	180
	41.5 D.	90

The evidence is that there is a condition of curvature hyperopia, since the ophthalmometric findings showed corneal powers of about 5 diopters less than the normal cornea.

Case No. 2. A hyperopic correction of 3 diopters in the case of a patient 45 years of age was obtained by the retinoscope. The ophthalmometric findings were:

Eye	*Power*	*Meridian*
Right	47.5 D.	180
	48.0 D.	90
Left	47.5 D.	180
	48.0 D.	90

These findings evidenced the fact that the hyperopia was, in all probability, not of a curvature nature but due either to lesser lenticular power or shorter axial length as compared to the average eye.

Case No. 3. A young woman, 33 years of age, was given the following correction for general wear: O.D. – 4.75 D.S. ⊂⊃ – 3.00 cyl. ax. 170 and O. S. – 1.25 D. S. ⊂⊃ – 1.25 cyl. ax. 25. The ophthalmometric findings were:

Eye	*Power*	*Meridian*
Right	42. D.	170
	44.5 D.	80
Left	42.75 D.	30
	44.25 D.	120

The corneal astigmatism amounted to 2.50 diopters with the rule in the right eye and 1.50 diopter in the left. Moreover, the curvatures of both eyes are less than for the average eye and clearly indicate that the myopia cannot be attributed to high corneal refractive powers. An inspection of the right eye indicated the presence of a slight breaking away of tissues at the temporal side of the disc. We are, therefore, rather positive that we are dealing with a condition of progressive myopia. Likewise we see that, in spite of the anisometropia present, the curvatures in the principal meridians of the two eyes are practically the same.

Irregular Astigmatism

Before the days of the modern ophthalmometer and other methods of diagnosis no class of refractive cases was more troublesome or difficult to handle than those with irregular curvature of the cornea. In the ophthalmometer, the images of the mires are of value in detecting irregular astigmatism, for they show distortion of the corneal image and the irregularity of the outlines of the mires when corneal irregularities exist. Such irregular astigmatism is also shown when there is no position of the mires in which the corneal reflections can be made to form one continuous line.

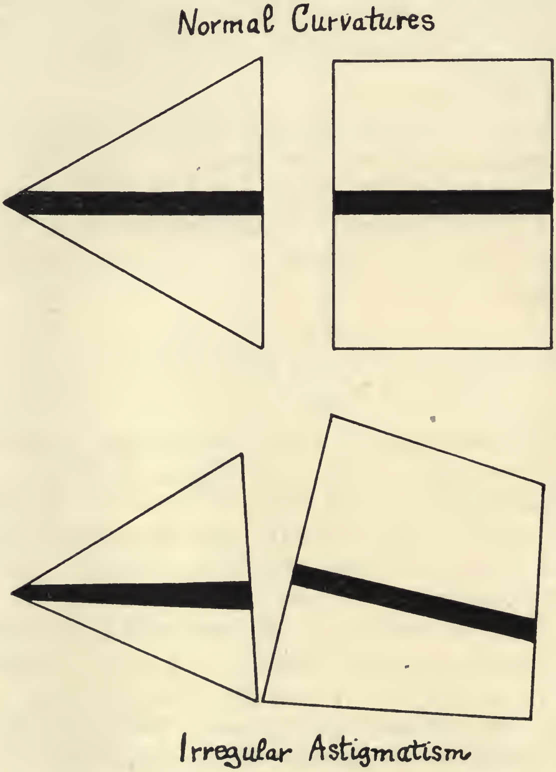

Figure 10. Upper diagram shows the normal reflections of mires in a principal meridian. The lower diagram shows the distortion in a case of irregular astigmatism.

This condition of affairs is roughly diagrammed in the figure given below, in which the upper illustration shows the normal condition of affairs while the lower diagram attempts to represent the distortion with lack of continuity of the central lines of the mires in irregular astigmatism. The best procedure, then, is to find the position of nearest approach to normal corneal reflections in two meridians as nearly at right angles to each other as possible. Or, to state it another way, regular astigmatism may be present in addition to the irregular form: there are then, in general, two positions at which these lines become more nearly continuous and straight and afford more nearly normal contact than elsewhere, thus indicating the meridians of the regular astigmatism.

The ophthalmometric examination is so delicate in the distortion test through the images of the mires that the smallest irregularities of the corneal surface may be detected. Following such an examination, there should be made a close inspection of the surface of the cornea by oblique illumination and an examination for minute opacities, facets and pits. Likewise, the ophthalmoscopic examination may afford

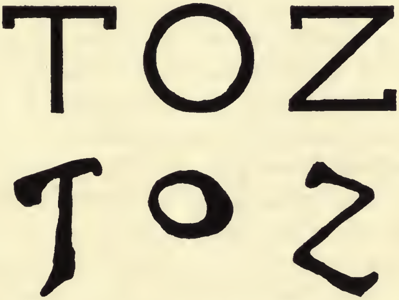

Figure 11. The upper row of letters is a reproduction of a well-known set of letters on a test-card; the lower set represents these letters as diagrammed for us by the patient in a case of irregular astigmatism.

evidence of the presence of such irregularities, for the writer has had cases in which, when viewed at the proper angle such as to include the irregularity, a doubleness of optic disc, etc. was visible. Subjectively the condition may often be detected by the distortion and grotesque forms which the larger letters in our test charts assume. One or two patients have sketched these for us and we are appending one set taken from our history cards. The first row of letters represents normal conditions; the second set as seen by this patient.

In passing, let it be said that we have found that the use of the stenopaic slit in these cases of irregular astigmatism, with the determination of the meridians of best and poorest vision and their independent correction, to be ultimately combined into a sphere-cylinder combination, has been of great service. And the ophthalmometer aided greatly in the location of these two meridians.

To illustrate the points we have been discussing we are citing two cases. It should be remarked that many, if not most, of these conditions of irregular astigmatism are the sequelae of various types of ulcers.

Case No. 1. A young man came complaining that there seemed to be a "veil", as he expressed it, in front of his eyes, and that he suffered from monocular diplopia in each eye (and hence binocular) always seeing a second less distinct object, such as a line of letters or type for example. He was wearing O. D. + 3.00 cyl. ax. 165 and O. S. + 2.25 cyl. ax. 45; without glasses the acuity in each eye was practically 2/10; wearing the corrections the acuity binocularly was a little better than 3/10. Ophthalmometric examinations revealed the characteristic appearances of a case of very irregular astigmatism; no continuity of the central line of the mires was possible. The nearest continuous meridian in the right eye was at 45° and in the left eye at 80°. The ophthalmometric examinations were as follows:

Eye	*Power*	*Meridian*
Right	49. D.	45
	43.5 D.	135
Left	47. D.	170
	50.5	80

These findings show astigmia of approximately 5.5 diopters in the right eye and 3.5 diopters in the left. The case, as finally worked out by the use of stenopaic slits, gave O. D. − 3.50 D. S. ⊂⊃ + 6.00 cyl. ax. 55, V = 8/10 and O. S. − 1.50 D. S. ⊂⊃ + 3.00 cyl. ax. 10, V = 8/10, indicating that the ophthalmometric findings, in so far as they gave a fair approximation to the amount of regular astigmatism mixed with the irregular, were a most valuable asset.

Case No. 2. A young man had his eye injured several years ago by the explosion of a pop-bottle. The eye was given immediate attention, and the healing was all that could be desired. At the time of the examination recited, he complained of "wavy" effects with this eye and that he could see half of words only. The left eye was, according to his statements, in good shape, but the two eyes did not work together well in the act of reading and other close work, as might be expected from the statements recorded above. The static retinoscopic examinations showed such irregular and confusing reflexes as to fail of any information: the same was true of the refractive examination by dynamic skiametry. The ophthalmometric examination evidenced some irregular astigmatism toward the temporal edge of the cornea but little if any in the direct line of sight. The findings were:

Power	*Meridian Measured*
37. D.	55
43.5 D.	145

indicating a corneal astigmatism of six and a half diopters; calling, *per se*, for its correction either − 6.5 cyl. ax. 55 or

+ 6.5 cyl. ax. 145. The subjective findings indicated that +1.50 D. S. ○ − 6. cyl. ax. 60 gave V = 30/50. The refractive assistance obtained through the use of the ophthalmometer in this and similar cases cannot be over-estimated; the ophthalmometric findings were the greatest asset in this instance.

Keratoconus

Keratoconus is a non-inflammatory conical protrusion of the center of the cornea and is due to a thinning of this membrane whereby it is unable to resist the normal intraocular pressure. Conical cornea causes myopia and astigmatism and seriously interferes with vision even after the best possible corrections with lenses. The most valuable objective test is that with the ophthalmometer. The retinoscopic procedures may be of value. The subjective tests

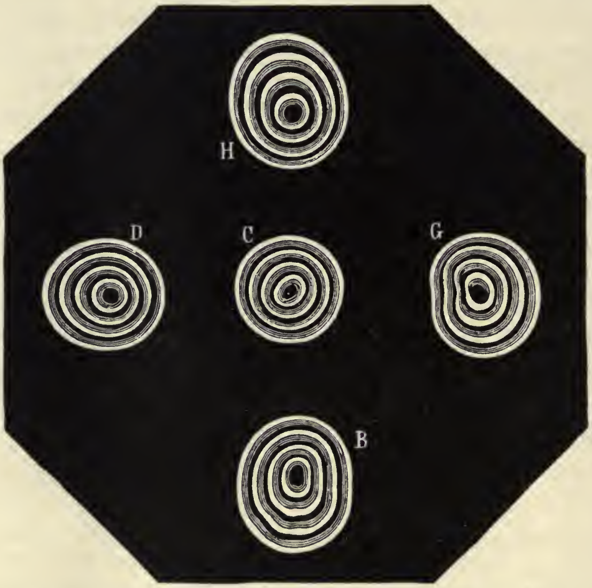

Figure 12. Keratoscopic figures of a cornea presenting a considerable astigmatism at the central part. (After Javal.)

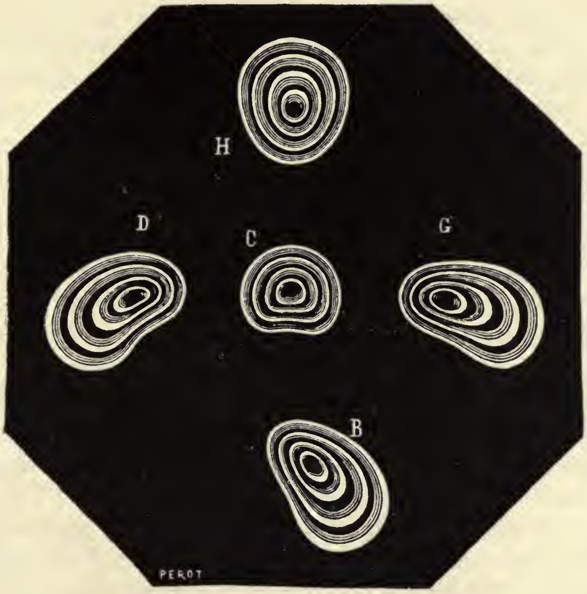

Figure 13. Images from the Placido's disc in a case of keratoconus. (After Javal.)

with the trial lenses are often facilitated by the employment of the stenopaic slit. In keratoconus there is always more or less irregular astigmatism. The ophthalmometer is not generally capable of locating the axes with exactness or of measuring their powers, but it does afford a method of close approximation. The ophthalmometer and the Placido's disc enable one to select the area in or near the visual area which is best suited for visual purposes. In the high amounts of astigmatism that commonly occur in conical cornea it is necessary to add an extra prism to the ophthalmometer. This decreases the sizes of the images of the mires one-half, but enables the operator to measure much higher degrees of astigmatism.

While the power of the normal cornea varies between 40 and 48 diopters, higher values are found in cases of conical cornea. Instances of 60 to 80 diopters are occasionally found: in fact, Cordiale found a case in which the curvature was about 100 diopters, corresponding to a radius of 3.4 mms. Various ophthalmometric examinations in such cases, made by Cordiale, show that the dioptric powers of the cornea, at points one or two millimeters to the nasal or temporal side of the visual line, change as much as 20 or more diopters, whereas in the normal cornea there is practically a uniformity of curvatures over this same region.

Case No. 1. The following very interesting case illustrates the excellent service rendered by the ophthalmometer. A man, 50 years of age, had worked for many years in a chain factory. His eyes had not been protected in any manner. Hot flying scales had struck his eyes with the result that the right cornea had been burned and an iritis had developed some thirty-five years previous to the examination. The vision in this eye was negligible as far as distance was concerned and was practically limited to the counting of fingers at close range. The visual act had therefore been carried on by the left eye until finally an opacity of the cornea in the line of vision and a cataractous condition of the lens in the left eye had set in and developed to the extent that peripheral vision only was enjoyed, and even this seemed to be abnormally low. The only apparent hope, at least within the near future, in this case lay in the help which might possibly be given the right eye. The ophthalmometric measurements were initially made and gave:

Power	*Meridian*
55	165
42	75

Hence, the ophthalmometer, in addition to showing the presence of some irregular astigmatism, evidenced about 13 diopters of regular astigmatism corrigible theoretically by means of + 13 cyl. ax. 165 or — 13 cyl. ax. 75 in order to reduce both curvatures of the cornea to equality. Static retinoscopy, especially after the assistance furnished by the ophthalmometer, was fairly easily carried out and gave − 5.75 D. S. ◯ + 15.00 cyl. ax. 170 and dynamic skiametry gave − 2.00 D. S. ◯ + 14.00 cyl. ax. 70. By means of − 5.50 D.S. ◯ + 12.00 cyl. ax. 165 the vision was raised to 30/50. For reading purposes − 2.00 D.S. ◯ + 11 cyl. ax. 170 (a change of 5° in the axis was invariably selected by the patient in comparison with the position of the axis as determined at distance) permitted of the reading of headlines, large type, etc. in newspapers. The subsequent history of this case is not recorded here, since the point which we desire to emphasize is the importance of ophthalmometric findings. Modern refractive methods do not pass up as hopeless any conditions, however irregular or beset with difficulties, until the last possible method of examination has been tried and has failed. Pathology in an eye may, of course, render void and useless the most skilfully made refractive findings, but we wish to record in the closing words of this paragraph our belief that the name of pathology has ofttimes been made to bear the burdens of ignorance in scientific refraction and all its ramifications.

Advantages of Ophthalmometric Measurements

As mentioned in other sections of this paper, the ophthalmometer is designed to measure the radius of curvature of the cornea and to thereby determine its refracting power. The facts which are obtainable through the making of these measurements include:—

(1) Whether the corneal curvatures are the same in all meridians or not: if there is no difference, then there is no corneal astigmatism.

(2) Whether the radius of curvature is shorter or longer than the average. This is of value even though no corneal astigmatism is found, for the reason that a difference of one millimeter in the radius of curvature of a cornea corresponds

practically to six diopters of refracting power. It is commonly found that an eye having a cornea with a radius of one-half millimeter or more shorter than the average is myopic: in turn, one with a radius of curvature one-half millimeter or more longer than the average is hyperopic. Hence, the ophthalmometric measurements may be of service in indicating refractive, curvature or axial hyperopia or myopia.

(3) Whether the cornea has a toroidal curve; if so, corneal astigmatism is present. The principal meridians and their powers may be located accurately. The operator will not be able to determine whether a plus or minus cylinder should be accepted by the patient, but he will be able to determine where to place the axis of the plus or minus cylinder indicated, should either be eventually accepted, in so far as corneal conditions are concerned. There are possible exceptions to this last statement, especially in cases of cyclophoria at close points when there is an absence of cyclophoria at distance. Of course, the reader is not to imply from the foregoing statements that the ophthalmometric findings as to axis are infallible: they simply show corneal conditions.

(4) We may determine whether irregular astigmatism or keratoconus is present or not and to what extent. Any asymmetry of this character will be readily detected, for the images of the mires will be distorted. Frequently the images of the mires lose all resemblance to the mires themselves.

(5) We may determine whether the corneas of the two eyes are similar or dissimilar and whether the corneal astigmatism, if present, is symmetrical or unsymmetrical. To illustrate: if the meridian of greatest refraction is at 90 degrees (or 180 degrees) in both eyes, the patient then sees vertical or horizontal lines sharply (dependent upon the error) without torting the eyes. If the meridians are 90 degrees and 70 degrees respectively, the patient will be

unable to see the same lines distinctly with both eyes unless he tilts his head some 10 degrees in order to bring the two principal meridians into something like symmetrical positions, or else the oblique muscles will have to tort the eyes in the interest of clear binocular single vision. It is likewise true that the condition of slightly blurred yet equal or similar images upon the maculae of both eyes is less destructive to good vision than the condition of a blurred image upon the macula of one eye and a sharp image upon the macula of the other. Great care is necessary to see that the cylinders are correctly placed in order that no tilting of the head or torting of the eyes (cyclophoria) shall be induced for the purpose of obtaining similar images upon the two maculae. Hence, we particularly desire that the eye remain in its position of rest. If the axes of the cylinders are incorrectly placed, asymmetrical meridians may be produced, causing the eyes of the patient to be torted or the head to be tilted, thereby producing more or less discomfort.

It is often of the greatest value to note the expressions of opinion of scientific men upon various phases of the work in which they are interested. Opinions from as widely separated geographical sources are equally to be desired: we may, therefore, be pardoned the insertion of a lengthy quotation from an address on "Errors of Refraction" (*British Journal of Ophthalmology*, Vol. II, June 1918) by Lieut.-Colonel R. H. Elliot of London, England. He says:—"The uses of an astigmometer, as they appear to me, are as follows: (1) The instrument will often give the exact axis of the astigmatism. (2) When the axes of greatest and least astigmatism are not at right angles with each other, it will point out the discrepancy and give both readings. (3) Though it only measures the corneal astigmatism, and though a correction has almost invariably to be made to its readings, it furnishes valuable data in a large number of cases. (4) In asthenopic patients, with low astigmatism against the rule, it will point out the defect unerringly, and indicate the need for a cycloplegic retinoscopy, even though the vision is fully normal. (5) In cases of high hyperopic and myopic astigmatism, which present great difficulties for satisfactory retinoscopy, its indications prove more than valuable in a large number of instances. (6) In cases with deep medial opacities, sufficiently dense to make retinoscopy unsatisfactory, the correction of the corneal astigmatism, made by the aid of the astigmometer, may prove of much use. (7) In the routine examination of presbyopes, before prescribing a reading correction, astigmometry shortens the examination and adds precision to it. (8) In children, restless patients, and imbeciles, it sometimes proves a valuable auxiliary to, or even substitute for, retinoscopy. (9) As a means of ascertaining whether any surgical procedure or corneal affection alters the corneal astigmatism, it is unrivalled. Incidentally, its use in this connection sometimes furnishes information of great interest. May I cite one example? The corneal astigmatism, found after cataract extraction as shown by the astigmometer, is markedly in excess of the total astigmatism present. There is, therefore, a compensatory factor in action and this, I think, is to be sought at the anterior surface of the vitreous. I am not aware that this observation has ever been put on record, but any of you can confirm it for yourselves. (10) It will unerringly and immediately show the presence of slight nebulae of the cornea, irregular corneal astigmatism, disparities between the curvature of one and another part of the cornea, such as produce scissor movements in retinoscopy, and the existence of conical cornea".

Furthermore, there are the reports of John Rowan (*British Medical Journal*, 1912) in which the astigmatism in a thousand eyes was measured, first by the ophthalmometer of Javal and Schiötz and then by retinoscopy, with atropin or homatropin as a cycloplegic. The results of his measurements show that, out of the one thousand eyes examined, *the total astigmatism and the corneal astigmatism were in* *agreement in nearly fifty per cent.* of the cases. This is surely an interesting and valuable conclusion and comes as a brisk rejoinder to those who minimize the value of the ophthalmometer in ocular refraction to the point of stating that it is of no value whatever.

A Discussion of the Relations between Corneal and Total Astigmatism with Some Details as to Factors which may Account for the Differences

Quite a difference is often found between the ophthalmometric and subjective measurements. This was first pointed out by Donders and later by Knapp who attributed—with a fair degree of accuracy in many cases—this difference to an astigmatism of the crystalline lens which would act in a contrary direction to that of the corneal astigmatism. Javal, Pflüger, Tscherning and others have investigated the relations between corneal and total subjective astigmatism.

The rules of Javal, commonly accepted by most investigators and refractionists as being a first order approximation to the truth and hence of much value, are:—

(1) If there is no ophthalmometric astigmatism, we generally find a slight subjective astigmatism against the rule. This condition would, of course, call for corrections involving plus cylinders at or in the vicinity of 180° or minus cylinders at or in the vicinity of 90°.

(2) If the ophthalmometric astigmatism is against the rule, the subjective astigmatism is usually against the rule and of a greater amount.

(3) If the ophthalmometric astigmatism is with the rule and of a value intermediate between one and three diopters, the subjective astigmatism generally differs only slightly from it.

(4) If the ophthalmometer gives an astigmatism with

the rule and greater than three diopters, the subjective astigmatism is also with the rule and frequently greater.

Javal expressed the difference between the subjective astigmatism (As_S) and the ophthalmometric astigmatism (As_C) by the empirical rule or formula that

$$As_S = k + p.As_C$$

in which k and p are two constants, k being approximately 0.5D. *against the rule* and p having a value of 1.25, hence a multiplying factor a little greater than unity. We can physically and physiologically account for the significance and value of the term k but we know of no investigator or writer who has satisfactorily explained why the factor p should be greater than unity. Since k has a value of 0.5 D. against the rule, it is necessary to add it to the ophthalmometric finding in cases of astigmatism against the rule and to subtract it in cases of astigmatism with the rule.

The formula gives the following numerical values which are found to check reasonably well in ordinary, everyday practice:

	Against the Rule			*With the Rule*					
Ophthalmometric Astigmatism	2	1	0	1	2	3	4	5	6
Subjective Astigmatism	3	1.75	0.5	0.75	2	3.25	4.5	5.75	7

Certain factors must be considered when discussing the reasons why ophthalmometric astigmatism and the total astigmatism as found by other methods are often not in conformity with each other: (1) the positions of the lenses in front of the eyes and the influence of the distance of the correcting lens from the eye; (2) deformity of internal surfaces or astigmatism due to the forms of the internal ocular surfaces; (3) normal or abnormal lenticular astigmatism; (4) astigmatic accommodation; (5) astigmatism by incidence and crystalline lens obliquity; (6) spherical aberration and the astigmatism in the different zones of the cornea and (7) contraction of the recti muscles.

(1) *The influence of the distance of the correcting lens from the eye.* Years ago Javal and Pflüger carried out corrections of astigmia subjectively, the first named investigator using plus cylinders whereas the second used minus cylinders. The subjects were examined in common, and the ophthalmometric data afterward compared with the subjective astigmatic findings. It was found that Javal obtained higher corrections than Pflüger throughout the whole gamut of astigmatism tested. The astigmatism of the eye was, under their methods of testing, constant: hence the difference in their cylindrical corrections for various ophthalmometric determinations is due, in part at least, to the effectivity of plus and minus corrections situated at a certain distance from the eye. We must, therefore, take account of the change of effectivity of cylinders as they are placed in advance of the cornea and as they are convex or concave: hence, apparent changes in the astigmatism of the eye may arise from optical sources. To illustrate: Suppose there is found with the ophthalmometer 4D. of actual corneal astigmatism: there will then be theoretically required, if the eye is otherwise emmetropic and the cylinder is placed about 20 mm. from the principal plane of the cornea, either a cylindrical correction of + 3.70D. or – 4.35 D., dependent upon the nature of the astigmatism. (Vide: *American Encyclopedia of Ophthalmology*, Vol. XIII, pages 9814 – 18 and 9873 – 76, and Sheard: *Physiological Optics*, pages 94-98 and 151-157.)

(2) *Astigmatism due to the forms of the internal ocular surfaces.* About seventy per cent of all corneas show an astigmatism of from 0.5D. to 1D. at the anterior corneal surface. We know but little about the posterior surface

but the experiments of Stadfeldt and of Tscherning show that the vertical meridian of the posterior surface of the cornea possesses a more pronounced curvature than the horizontal meridian, whether the condition *in toto* is one of astigmatism with or against the rule. Since the posterior surface is concave, this greater curvature in the vertical meridian will cause an astigmatism against the rule. It may well be that this is the cause of the small subjective astigmatism against the rule, generally found subjectively when the ophthalmometric findings show no anterior differences in various meridians.

Tscherning, Stadfeldt and Awerbach made measurements upon the crystalline lens, using an instrument known as the ophthalmophakometer. The anterior surface of the crystalline in all cases examined showed a direct, or with the rule, astigmatism while the posterior surface often exhibited the inverse, or against the rule, type. We are to judge in a general way from the results of their experiments that the crystalline surfaces are more spherical in form than the cornea.

(3) *Lenticular astigmatism.* Javal, Nordenson, Schiötz and others have shown that the lenticular astigmatism as a rule amounts to about half a diopter. This may be called the normal lenticular astigmatism, just as we have about the same amount of astigmatism normally present in the cornea. In general the two neutralize each other in the sense that they offset each other, producing the equivalent spherical error.

Dr. Davis (Essay on Refraction and Accommodation of the Eye: *The American Encyclopedia of Ophthalmology*, Vol. XIV, page 11164) writes: "The lenticular astigmatism, as a rule, amounts to about 0.50D. to 0.75D., as proved by abundant statistics, and it has been shown that, in actual practice, the corneal astigmatism is diminished or increased that amount, according as the astigmatism is with or against the rule. The most reasonable explanation to be given for the necessity of deducting 0.5D. to 0.75D. from the reading of the instrument when the astigmatism is with the rule and adding a like amount when the astigmatism is against the rule is the assumption that in corneal astigmatism with the rule there is usually associated a lenticular astigmatism of 0.50 to 0.75D. in the same meridian, but of an opposite kind, thereby neutralizing that amount of corneal astigmatism. In astigmatism against the rule there is, on the other hand, a lenticular astigmatism of 0.50 to 0.75D. in the same meridian and of the same kind, thereby adding that amount to the corneal astigmatism. This can be explained in another way. In corneal astigmatism with the rule the lenticular astigmatism may be of the same kind but in a meridian at right angles to the corneal astigmatism; in which case, if the meridian at error in both the cornea and lens were myopic, a simple myopia of 0.50 to 0.75D. would be produced. . . . However, the first explanation is more likely to be the true one and, in fact, actual measurements (Donders) have shown it to be true; and the ophthalmophakometer confirms this view."

(4) *Astigmatic accommodation.* Dolrowolsky first expressed the idea that astigmatic persons could partly correct their defect through an irregular or non-uniform contraction of the ciliary muscle, thus producing a deformity of the crystalline lens in the opposite direction. Some experimenters and clinicians admit this possibility and others do not. There are a considerable number of physical facts against the acceptance of astigmatic accommodation. Still these and other facts do not bar its existence. It is entirely possible from anatomical standpoints, since it is possible that a part of the filaments which go to the ciliary muscle may be in a normal condition, while others may be partially paretic or insufficient or, again, over-active, thus producing irregular action on the zonula. And again, subjectively no astigmatism may be evidenced, the vision being 20/20 easily,

while all objective tests show the presence of a decided astigmatism, indicating an astigmatic accommodation. Furthermore, we know from clinical experience that the correction of an objective astigmatic condition lessens discomfort and relieves ocular headaches in many cases although no improvement of the vision may result. (*vide*, Howe: *Muscles of the Eye*, and Sheard: *Physiological Optics*, page 144).

(5) *Astigmatism by incidence and lens obliquity*. The pupil of an eye is ordinarily centered with respect to the axis of the ocular system. The point of fixation is, however, upon the visual axis. The angle between the optical and visual axes is generally known as the *angle alpha*, usually of the order of about 5 degrees. Hence, even though the incident beam along the axis should be devoid of astigmatism, the beam along the visual axis will not be. By virtue of this angle alpha an "against the rule" astigmatism arises which is, on the average, about one-half to three-quarters of a diopter. The following table is self-explanatory upon this point:

	Angle Alpha (*Degrees*)				
	1	3	5	7	9
Corneal Astigmatism	0.02 D.	0.13 D.	0.35 D.	0.66 D.	1.11 D.
Lenticular Astigmatism	0.01 D.	0.05 D.	0.14 D.	0.26 D.	0.44 D.
Total Astigmatism (Diopters)	0.03 D.	0.18 D.	0.49 D.	0.92 D.	1.55 D.

Another form of astigmatism due to incidence may be designated as astigmatism due to lens obliquity. For example, if the crystalline lens should be tilted about its horizontal axis, there would be produced thereby an astigmatism against the rule. A tilting of the crystalline lens *in situ* of 10 degrees would cause an astigmatism of about 0.5D.

The Bowman muscle and not the ciliary is involved in the placing and in the holding in position of the crystalline lens. Savage (*Ophthalmic Myology*, 2d edition, pp. 637–38) discusses in a very entertaining manner his own condition of astigmatism, both from the ophthalmometric and subjective testings over a period of years, and attributes the differences in large measure to the lenticular astigmatism produced by a tilting of the crystalline lens.

(6) *Spherical aberration.* In quite high degrees of astigmatism the images of the mires are affected by spherical aberration. On this account there is recorded an excess of error. Leroy and Reid insist that a proper reduction in the astigmatism measured by the ophthalmometer must be made if it is to accord with that found on subjective examination.

(7) *Contraction of the recti muscles.* By voluntary action the recti muscles, in a few cases, alter the corneal astigmatism. Davies (Essay on Refraction and Accommodation of the Eye, *American Encyclopedia of Ophthalmology*, Vol. XIV, page 11168) reported in 1895 the case of a patient who had a corneal astigmatism with the rule of 0.5D. which could be, by voluntary action of the recti muscles, increased to 2D. in the right eye and to 1.5D. in the left eye. Under a cycloplegic he could still increase the astigmatism in the right eye to 1.5D. and in the left eye to 1D.

Abstracts and Reviews

Experimental Cataract From Ultra-red and Red Rays

Dr. A. Vogt

SUPPLEMENTING his former studies which showed that the short ultra-red waves of our artificial light sources reach the lens and retina in even greater amounts than the visible light, Vogt succeeded with the apparatus, which he describes very well, in producing a total cataract in the intact lens of an adult black rabbit by a three hour exposure. In a young rabbit the upper part only of the lens showed opacity, due, supposedly, to the cone of light impinging in this part principally.

The opacity is situated partly beneath the capsule, but mainly in the first zone of discontinuity, and affects the anterior and the posterior parts of the lens equally. The two areas of opacity are connected. Another pigmented rabbit showed opacity in the anterior upper part of the lens. In albinotic rabbits these effects could not be produced in the time mentioned above.

From his findings Vogt deduces that glassblowers' cataract is due to the ultra-red and red rays; not, as was formerly assumed, to the ultra-violet rays. He hesitates to draw conclusions as to the etiology of senile cataract from his findings, and says that they do not explain the occurrence of cataract in India and other hot countries at an earlier age (if such be the case). Neither does he feel able to say that cataract may not be caused by other than ultra-red rays, for instance by visible rays. A further effect of exposure to this ray mixture is the bleaching of the pigment of the pupillary edge; after a few weeks one could see the pigment scale off and fall into the anterior chamber. A regular accompaniment of the exposure is the paralysis of the sphincter of the iris, and the whitening of the hairs of the brow.

(Abstract translation from the *Correspondenzblatt für Schweizer Aerzte*, V. 44, October 30, 1919, *American Journal of Ophthalmology*, Vol. 3, No. 1, 1920.)

Transmission of Colored Light Through Fog

C. L. Utterback

THIS investigation covered a study of the transmission of light of different wave-lengths through fog. Measurements were made on thick, medium and slight fogs; a medium fog is about the density of a moderate fog as ordinarily understood. The apparatus used in this work consisted of a tube of proper dimensions with suitable optical end pieces so arranged and connected with an air pump and a reserve jar of large capacity that rapid expansion with the resultant cooling would produce a fog. The intensity of the beam entering the chamber, both before and after the production of the fog, was measured with a Macbeth illuminometer. The various wave-length ranges were obtained by means of absorption curves. About a dozen different screens were used. An accuracy of observation of approximately one per cent is claimed. The ratio of the illumination in foot-candles with no fog to the illumination with fog gives the percentage transmission.

The experimental results show that the transmission is highest for wave-lengths from about 5300 t. m. to about 5900 t. m. and that it falls off very rapidly toward the red but not so rapidly toward the blue. Dr. T. Ewan (*Proceedings Royal Society of London*, Vol. 57, pp. 117–162, 1894) reported investigations on the transmission of colored light through pure water which are similar to those here reported.

Curve I is the curve obtained for the transmission through fog. Curve II is the one obtained by Dr. Ewan for trans-

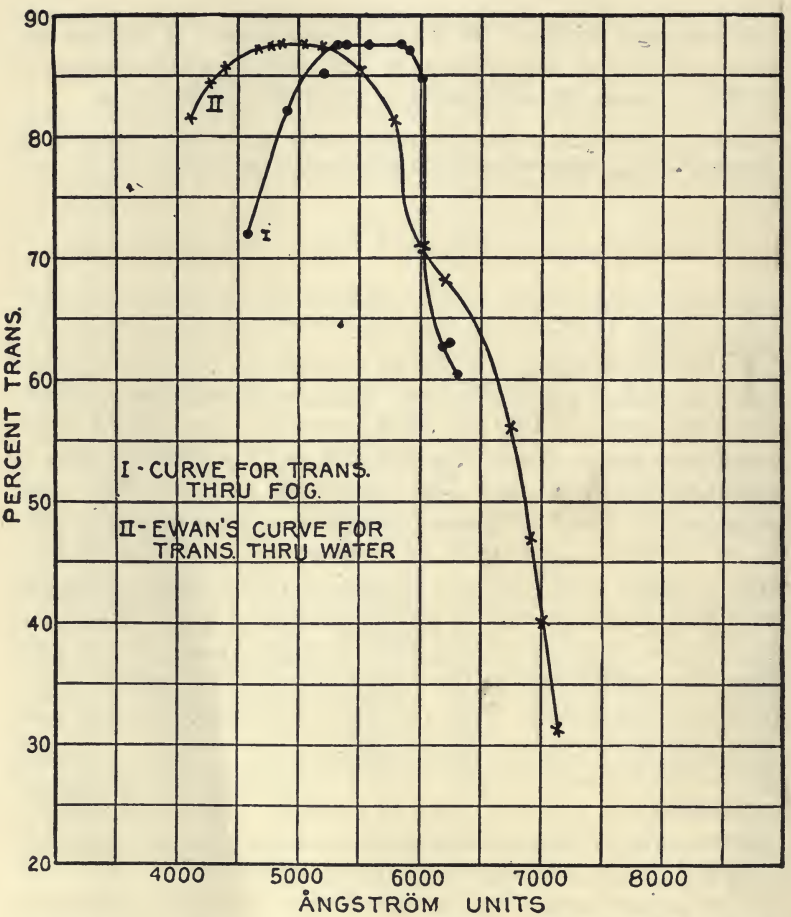

Figure 1. Curves showing the transmission of various wave-lengths by fog and water.

mission through pure water. The maximum transmission for pure water is displaced toward the violet with respect to the maximum transmission, through fog as found by Utterback.

The mean wave-length for maximum transmission through fog is found to be at about 5620 t. m.

The conclusion is reached that any light will have its maximum transmission through fog if the light is composed of wave-lengths from 5300 to 5900 t. m. only.

(Abstracted from *Transactions of Illuminating Engineering Society*, Vol. XIV, page 140, 1919.)

Cataract Probably Due to X-Ray Exposure

Oscar Wilkinson, A.M., M.D.

THIS is a case of double cataract in a woman only forty years of age. The history of the case was negative up to two years ago. Examination revealed nothing abnormal about the eyes except a slight irritation of the conjunctiva, a low degree of astigmatism and a slight clouding of both crystalline lenses, more marked in the left eye. R. V. equals 20/20 – 2, and L. V. equals 20/20 with a low cylindric correction. A general examination of the patient by her physician revealed: blood normal, urinalysis negative, examination of tonsils, teeth and sinuses negative and no digestive disturbance. No physical abnormality was noted except a very extensive lesion of lupus erythematosus, which covered a considerable portion of each cheek and a part of the nose.

The author, in his search for an etiologic factor, learned from her that during the first two and one-half years prior to her first visit to him, she had had her face exposed to the X-ray for the treatment of the lupus erythematosus. The first year she was treated every ten days, making a total of 36 exposures that year and the second year and a half she had a treatment every two weeks, which would make 36 treatments. Allowing for some lapses or broken dates it would be safe to estimate that she had more than 60 treatments; and at no time were the eyes protected with lead sheet, leather, or any filter. What is probably more significant, she states that she had a habit of looking at the small light in the Coolidge tube while she was being treated, thus exposing the lens to the ray with no protection except the transparent cornea and the aqueous humor.

Cataract has been produced by radiated heat. Cataract occurs more frequently in furnace workers and bottle workers than in other occupations less exposed to excessive heat.

In Mexico and other sunny climes, cataract is much more frequent than here in the United States, and this has been attributed to the excessive sunlight. The natives of India are more frequently affected with cataract than we are here, and this has been ascribed to the excessive sun and heat and also to the fact that the cataracts in the natives of India contain an unusual amount of silicon.

Verhoeff and Bell were of the opinion that heat had more to do with the production of cataract than light. Burge made some experiments in which he showed that a lens exposed to ultra-violet rays, especially when the lens is charged with certain salts of calcium, magnesium or silicon, becomes opaque.

The elements in this case which would cause one to consider the X-ray as a possible etiological factor are:

1 Double cataract developing simultaneously in a case so young, without any constitutional or local evidence of disease.

2 The excessive amount of X-ray exposures, more than 60 treatments having been given.

3 No filtration of the ray, as evidenced by the fact that the patient could look at the small light in the Coolidge tube.

4 The eyes being uncovered, open and not even having the protection of the lid with the skin-muscle and cartilage.

(Abstracted from *American Journal of Ophthalmology*, Vol. III, p. 435, June, 1920.)

The Maddox Rod Screen Test

Captain Pere Dolman, M.D.

THE Maddox rod test was used as a test for the detection of heterophoria in the primary position of those applying for service as fliers. Its great ease of application and simplicity recommended its use. But all practitioners know of some points which tend to call into question the accuracy of the Maddox rod test, and it is with such criticisms that the writer deals. Amongst the criticisms cited by the writer and which are found recorded in searching American ophthalmic literature are those of (a) Duane, who says that the test is not as reliable as the screen and parallax tests and that the amount of excessive esophoria is of the order of one degree, (b) Howe rates this test as third in clinical value in his *Muscles of the Eye*, (c) Stevens touches upon a vital point when he says that the tendency of the line to fuse with the light is so great that orthophoria is often found when heterophoria exists, (d) Weeks points out the difficulties some patients have in seeing the line, while (e) Weymouth concludes that the Maddox rod shows an excessive amount of esophoria.

Dolman used a deZeng phorometer equipped with two Maddox rods and Risley rotary prisms, and a spot of light from a frosted Mazda lamp enclosed in a chimney with an iris diaphragm and adjustable as to position. Tests were made at 20 feet with the eyes in the primary position. The screen and parallax tests of Duane were used as control experiments.

The investigations upon the Maddox rod are reported under the following heads:

I Excessive esophoria
II Fusion tendency
III Instability of line
IV Inability to see the line

I. *Excessive esophoria.* One hundred men were examined and the Maddox rod and screen and parallax tests applied. Of these about 75 per cent showed ½ to 2Δ more esophoria or less exophoria by the Maddox rod than by the control tests. The possible causes of the excessive esophoria were limited ultimately to two: (a) latent hypermetropia and (b) false projection of the line.

a. *Latent hyperopia.* Emmetropes were selected and artificial hyperopia produced by adding concave lenses. In these tests it was found that the addition of a great variety of lenses to one or both eyes of the observers confirms the conclusion that a hypermetropic condition of the light fixing eye, by stimulating accommodation and convergence, always affects the findings of the test in favor of esophoria. Also, it was found that the eye fixing the light controls the finding. Experiments emphasize the necessity of having *the patient wear his refractive correction during the test for heterophoria.*

b. *False projection of the line.* In no instance in Dolman's experiments did the observer report that he believed the line of light to be as far away as the light. In many cases the line of light was estimated as being a few inches or a foot or so from the face. If the observer, therefore, visualizes the line nearer than twenty feet and focuses upon it where he imagines it to be, the accommodative effort he makes produces a convergence. This would naturally increase the esophoria shown by the test. Various experiments indicated that an indistinctly seen line—whether from reduced visual acuity, irregularities of the Maddox rod or what not—causes the observer to try and bring the line into sharp focus. This would result in esophoria if accommodative effort is made. The obvious procedure in this test is, therefore, to keep the observer's attention fixed as completely as possible on the light.

II. *Fusion tendency.* The investigations made indicate that the spot of light and the line projected by the Maddox rod form retinal images sufficiently dissimilar in form to prevent actual fusion in the measurement of esophoria and exophoria. The fusion tendency is increased by four conditions briefly discussed in the following paragraphs.

a. *Exclusion of extraneous retinal images.* When the room is darkened and only a bright light and line of light are present there is a strong tendency to fusion, thus avoiding the double images in the attempt at fusion. When the room is sufficiently bright that extraneous images of numerous objects are present, the tendency to fusion is in general decreased.

b. *Horizontal and vertical lines in the background.* The vertical lines of doors and window casings, cabinet edges, etc., even when situated twelve inches or more away may be fused with the light. "The most vicious is that of the vertical standard made to support the lamp used in the test."

c. *Additional sources of light.* The spot of light used for testing should be the only source of illumination visible to the observer. Other sources of light cause supernumerary lines, any one of which may be fused with the spot of light and hence give a false image.

d. *Intensity of the point of light.* An intensely bright source causes an intensely bright line to be formed and the tendency to fusion is increased, especially if the room is very dark. A moderately intense light for this test is ample.

III. *Instability of the line.* A "wavering" or dancing of the line is reported by observers. Hence in the Maddox rod test for esophoria and exophoria, the line lacks stability. An experimental study showed that the movement was checked when the observer concentrated his attention and fixation on the light, disregarding the line as much as possible. And, *vice versa*, fixing the line of light. The movement of the line of light is probably due to an effort to fix both the line and the light at the same time, or as a result of fixation which alternates between the light and the line. This may be due to fusion tendency, unequal hypermetropia and false projection of the line.

IV. *Inability to see the line.* The causes of failure to see the line are discussed under the following heads:—

i *Malposition of the Maddox rod.* A single Maddox rod must be carefully adjusted to bring the line in the field of view. A more distinct line is always obtained when the rod is placed close to the eye.

ii *Bright illumination of the room.* In a brightly lighted room the line is not easily seen in contrast with the surroundings. The test is best made in a semi-darkened room.

iii *Dimness of the spot of light.* A bright source of light, diffused by ground glass, is most suitable with a screen of from 8 to 10 mm. diameter.

iv *Non-essential sources of light.* When sources of light, non-essential to the test, are located in front of the observer, several lines may be seen by the patient.

v *Poor vision in one eye.* The eye covered by the Maddox rod may have such poor vision that the line cannot be seen distinctly. The obvious remedy is to put the rod before the better eye.

vi *Habitual suppression of one image.* When the image of the non-fixing eye is habitually suppressed, the Maddox rod test fails.

vii *Poor vision in both eyes.* When the visual acuity is greatly reduced in both eyes, the test may fail because neither eye can see the line distinctly.

The writer gives some details of his method of using the Maddox rod screen test at six meters. He writes:

"The observer is seated facing the light, which is at the height of his eyes and six meters distant. The Maddox rod may be held in position by a trial frame and the measurements made with square prisms or those found in the trial case. The test is much simplified and greatly facilitated by the use of a modern phorometer-trial frame, equipped with a double multiple Maddox rod and a double Risley rotary prism. This apparatus is brought closely in front of the observer's eyes and adjusted to a horizontal position by means of the spirit level. The phorometer is not used to measure the amount of heterophoria because its binocular prisms deflect the visual axes of both eyes and consequently leave neither one in the primary position. Both the Maddox rod and the rotary prism are swung into position before one eye, allowing the other an unobstructed view of the light. It is a good idea to set the rotary prism 4Δ or 5Δ off the zero mark in order to deflect the line at the beginning of the test.

"A card about 6 x 9 cm. is used as a screen. This is moved from one eye to the other a few times to ascertain if the observer sees both the line and the light. If the line is not seen readily, the Maddox rod is readjusted by centering it carefully in front of the pupil. Some further darkening of the room may be necessary to render it visible.

"When the observer sees both the line and the light easily, the test is begun by holding the screen in front of the Maddox rod to shut out the image of the line. The observer now sees only the light. After he has fixed it for several seconds, the screen is removed for an instant and quickly replaced. In that brief interval the observer should see the line and be able to locate it with reference to the light. After one or two brief exposures, he will be able to say in a test for lateral imbalance that the line is to the right or left of the light or possibly through it. He is then instructed to grasp the milled head that rotates the prism and turn it to bring the line directly through the light. To enable him to do this, the screen should be removed from the eye at intervals and quickly replaced. Finally the observer will have rotated the prism enough to cause the line to pass through the light every time he sees it when the screen is removed.

The number of prism-diopters necessary to deflect the line through the light is read from the scale of the rotary prism.

"The results of the test will be more accurate if the eye that fixes the light is in the primary position and not deflected from it by a prism. It is for this reason that the measuring prism is placed always before the eye that is covered by the Maddox rod. The Risley rotary prism is convenient because it enables the observer to make the necessary prism correction himself.

"Attention is called to certain merits of the procedure described. One eye is permitted to fix the light while all vision of the line by the other eye is prevented except for brief intervals. The eye under cover takes a position that is influenced by a minimum of the innervation habitually required for binocular vision (2.8). The removal of the screen can be done so rapidly that the image of the line fails to stimulate the retina enough to cause readjustment of the visual axes in the interest of binocular vision, yet the exposure is long enough to permit the line to be seen for the purpose of the test."

Conclusions. 1 The Maddox rod test, because of its easy application and the simple nature of the observation required, enjoys a popularity and widespread use among ophthalmologists.

2 Studies of heterophoria, based wholly or in part on Maddox rod findings, are constantly being reported in ophthalmic literature in spite of some serious criticisms of the test.

3 The test has been condemned chiefly because it shows excessive esophoria, a tendency to fusion, and an instability of the line of light.

4 These faults of the test have been verified and the underlying causes determined.

5 The Maddox rod screen test, a simple modification of the usual procedure, gives results that are accurate and free from the above criticisms.

(Abstracted from *Archives of Ophthalmology*, Vol. XLVIII, No. 5, p. 503, 1919.)

On the Rod Screen Test

Mr. Ernest E. Maddox

FIRSTLY, all tests for ocular balance divide themselves into two classes: (1) Monocular occlusion tests, (screen tests, parallax, etc.), (2) Simultaneous vision tests, (phorometers, erect prisms, glass rods, etc.). I have an impression that all the first group tend to display greater divergence (or less convergence) than the second group, for the reason that in the first case one eye only stands "to attention"; whereas in the second both so stand, though the fixing eye of course more than the other. The convergence center, I think, is not so quiescent when both eyes are exposed, though dissociated, as when one is absolutely cut off. I have sometimes seen cases of exotropia in which the diverging eye, when covered by a screen, diverged several degrees further. The glass rod, therefore, in common with prism tests may be expected to show in many cases a trifle less convergence or more divergence than screen tests.

Secondly, some patients, instead of projecting the streak of light to the distance of the spot of light, project it nearer to themselves. This may tend to cause a slight convergence, stimulated by the apparent proximity of the line. I would go further, and say that, sometimes, even the point of light may appear nearer to the light than it really is, especially in a totally dark room. In ordinary life we are accustomed to think light is distant in proportion to the mist which intervenes; hence it is natural to suppose a very bright light nearer to us than it really is, unless the objects about it are sufficiently visible to correct this impression. Dr. Dolman has wisely made his light not too bright, and I have always advised the room to be only partially darkened. To get the best effect of all, a point of light in the center of a square yard of velvet in a room sufficiently darkened to avoid bright reflections from objects in it, gives the best result. To ensure accommodation a series of small figures cut out of white paper may be gummed to the velvet at intervals of a centrad from each other. In measuring hyperphoria the rods may be considered quite truly since the converging center is a negligible factor.

Thirdly, the variability of the line of light is of two kinds. The tonus of the converging center is a fluctuating quantity, so that the eyes wander more or less when fusion is suspended, and the movements of the light streak merely portray this to the mind, and are indeed an expression of the fidelity of the test. Another case of irregular movements of the line, however, of an undesirable kind is due to alternate fixation of the line, and of the point of light. To overcome this Dolman rightly recommends screening the disk of rods, with brief unscreening at intervals. The following quotations from my former writings may be of interest. "In addition, therefore, to placing the rod before one eye, it is sometimes well to exclude that eye, and expose it momentarily, that the line of light may be seen in a position answering to the deviation on exclusion." (*Ocular Muscles*, 1898, p. 357). Again, "Should there be any suspicion that in spite of the dissimilarity of the images, the mind makes some slight attempt to unite them, the glass rods, while in position, should be screened with a visiting card, and the patient be instructed to state the position of the red streak at the first instant of its appearance following the sudden withdrawing of the card. In this way we really discover the position of an eye excluded from vision." (*Ophthalmoscope*, Vol. x, p. 130.) I feel indebted to Dr. Dolman's investigation for indicating the desirability of doing this more frequently, or as a regular thing when very small departures from the normal require investigation. For considering deviations it is unnecessary, though for the sake of uniformity, it might be well to use it always with aviators.

Fourthly, the rod test has been credited with a tendency to fusion by some authors. It has always seemed to me remarkably free from this, since the line will sometimes stand almost touching the point of light, with no tendency whatever to coincide with it; the same being true when an extremely weak prism is used to transfer the streak to the other side of the point of light. It is taken for granted that complementary colors are used for the two eyes, the rod being red and the glass before the other eye being deep green. For color-blind patients the one might be blue and the other yellow.

Fifthly, in my earliest experiments with the rod I was greatly impressed with their ability to demonstrate low degrees of anisometropia, as shown by the different readings obtained when the disks on rods are placed before each eye in turn. When the rods first came into being I recorded somewhere that sometimes so little as a quarter diopter of difference between the two eyes can be thus detected, so that we might make some use of this test after the correction of refraction, when there is reason to suspect that the eyes are not equally fully corrected; for this purpose the rod screen test would be most suitable.

Sixthly, the chief advantage of the rod test over the prism test (double prism excepted) is that the reading is not apparently affected by slight inaccuracies in the position of the rods or of the head. Phorometers, however, are set so well that they do not come into this comparison. As shown elsewhere, any complication introduced by co-existing cyclophoria is best met by the glass rod.

In conclusion, the inaccuracies attributed by Dr. Dolman to the rods are all of a slight order which scarcely come into the range of ordinary practical work. They are practically "nil" in the measurement of hyperphoria. In practice we do not take much account of tiny horizontal deviations. For the competitive and comparative measurements of aviators, however, more strictness is essential, and here is a great value of Dr. Dolman's investigation. His recommendation of the more constant employment of the rod screen test for work of this kind is a distinct step in the right direction.

(From the *Archives of Ophthalmology*, Vol. XLIX, No. 2, p. 229, 1920.)

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Infra-red Radiant Energy and the Eye

M. Luckiesh

A NUMBER of years ago speculation was rife regarding the possibility that the absorption of infra-red radiant energy by the eye-media resulted in eye-fatigue. In fact, statements were made by eminent men that irritation and fatigue in the eye were due largely to this thermic effect. These statements were widely quoted, with the result that many have accepted this explanation of the source of irritation and fatigue of the eyes under artificial illumination. Although the assumption may be proved eventually to be true, the author is unaware of any definite experimental foundation at the present time. Without declaring for or against this assumption, the author, several years ago, computed the amounts of energy absorbed in the eye-media under various conditions of illumination and also the energy-densities throughout the optical path in the eye. As a consequence two papers (1,2) were published where they would reach those interested in lighting.

More recently there has developed quite extensively an opinion that eye-glasses, especially in the industries, should not transmit infra-red radiation. Therefore, it appears worth while to present some of these data within convenient reach of the physiologist and eye-specialist who doubtless are best fitted to supply experimental evidence regarding the possibility of infra-red radiation causing visual discomfort, eye-fatigue or permanent injury to the eye-media. At present infra-red radiation stands convicted purely upon circumstantial evidence and, although it is not the intention to present a brief for or against this radiation, it appears desirable to show the type of data upon which the conviction is based.

Crookes (3) inferred "that it is to the heat rays rather than to the ultra-violet rays that glass workers' cataract is to be ascribed" because these rays (ultra-red) are "present in the radiation from molten glass in far greater abundance than the ultra-violet rays." A number of questions of fundamental importance immediately arise. First, and of primary interest, is the question of the existence of glass blowers' cataract. The author has not encountered any qualified individuals in the glass industry who admit that cataract is prevalent among glass blowers. Furthermore, even though such prevalence be admitted for the sake of analysis, there is still the possibility that the causes when traced to their source may lead the investigator far from the molten glass into the other conditions of working or living(4.) Infra-red radiation may be found to be effective in causing cataract but possibly only in conjunction with some other agency or condition. In fact, it may be completely exonerated in the case of glass workers because ultra-violet radiation is emitted by molten glass as Crookes himself determined. Spectrograms made by him on photographic plates extended into the ultra-violet as far as 0.3345 μ when the exposure was prolonged sufficiently, but because of the low intensity of ultra-violet radiation compared with that of infra-red radiation, Crookes inferred that the blame must be attached to the latter. This is unphilosophical even when viewing the situation superficially, and is extremely so when considering the chemical activity of ultra-violet radiation with the comparative ineffectiveness of infra-red radiation in this respect.

The properties of radiant energy are not well defined as to wave-length. For example, the chemical effect of ultra-violet radiation varies with the wave-length and this variation varies with the chemical process. Furthermore, it is misleading, for example, to state that ultra-violet radiation is chemically active; that visible radiation arouses the sensation of luminosity; and that infra-red radiation is "heat" energy. Either directly or indirectly these various radiations have many properties in common. When measured as heat energy, radiations of all wave-lengths are alike—that is, they are readily converted into heat energy by absorption. A statement that infra-red radiation is the cause of cataract or eye-fatigue carries with it the possibility of condemnation of visible radiation on the same score because of certain similarities of the two radiations.

As shown later, if infra-red radiation is detrimental, owing to its heating effect under conditions which do not "burn" the skin or eye-membranes, then sunlight, owing to its enormous intensity, must be looked upon with suspicion. Even the visible radiation in sunlight is quantitatively large, owing to the extreme intensity, and, if the thermic effect of radiation is harmful, then sunlight is dangerous even when the water-vapor of the atmosphere has absorbed all the infra-red radiation.

Perhaps one of the reasons for the growing belief that infra-red radiation is harmful to the eyes may be found in attributing to this energy a destructive ability similar or analogous to that of ultra-violet energy. But such a property is not established for infra-red. In fact, it appears to be even less destructive to animal tissue than some of the visible radiation.

Notwithstanding this line of reasoning and the lack of direct experimental evidence, infra-red radiation has been condemned so often that many now believe it to be injurious. In fact, this conviction is so seriously accepted in many quarters that it is gaining rapidly and bids fair to be very generally accepted by those interested in eye-protection. This is illustrated for example by a recent technical paper (5) containing excellent data under the title, "Glasses for Protecting the Eyes from Injurious Radiation." Although the authors in their introductory remarks call attention to the lack of proof "that infra-red rays have other than a thermic (if any) effect," the data presented largely pertain to infra-red radiation. To the indiscriminating, the title of the paper containing, for the most part, data pertaining to the infra-red radiation, carries with it a strong implication if not a complete conviction that infra-red radiation is harmful to the eyes even for intensities too low to "burn" (in the ordinary sense) the skin and eye-media.

When considering vision, the infra-red radiant energy is at least useless and it is well to dispose of it if this can be done without too much expense and without injustice commercially. The brief discussion presented in the foregoing paragraphs does not aim to exonerate infra-red radiation but to focus attention upon the lack of experimental evidence. Many are now capitalizing this (at present) unfounded suspicion, and therefore this is an important problem confronting those interested in the care of the eye.

The data presented in this paper do not directly reach the root of the problem, but they are of considerable importance. Energy quantities and densities in the eye-media are established herein and should aid the physiologist or investigator who is interested in the question. This paper is confined purely to the physical aspects of spectral energy-distribution in illuminants, of the absorption by the eye-media, of optical laws, of luminous efficiency of illuminants, etc. The radiation from the theoretical "black-body" at various temperatures is considered and industrial processes involving high temperatures may be compared in terms of these data because most bodies emitting radiant energy by virtue of their temperature may be placed at least approximately on the black-body scale. In fact, it is enlightening and not difficult to arrange industrial processes approximately on a temperature scale according to the approximation of their emitted radiation to that of the theoretical black-body.

Anyone familiar with the spectral distribution of energy in the radiation from ordinary light-sources is certain that less energy per lumen is incident upon the eye as the temperature of the radiator is increased, provided that the light is due to purely temperature radiation. The computations in this paper will be confined to purely temperature radiation or radiation from bodies which deviate but little from it. Just what relative amounts of energy are absorbed in the various eye-media and how the amount of absorbed energy varies with the temperature of the source have not been determined, although Vogt(6) has described elaborate experiments which show roughly the transmission of the eye-media in various regions of the spectrum. His results roughly confirm the more refined experiments of Aschkinass(7). Fortunately, Aschkinass has clearly established the transmission of the eye-media throughout a wide spectral range and has obtained other data which enable certain computations to be made. He found that the various eye-media transmitted the visible and infra-red rays in the same manner as like thicknesses of water. The only discrepancies found were for the transmission of the cornea for the visible and "near" infra-red rays. The differences found in that case he attributed to the film which rapidly forms over the dead cornea, rendering it less transparent, for the absorption-bands were well defined and in the same position as for water.

The intensity of radiation after traversing any depth d, can be computed from the following equation:

$$I' = Ie^{-xd}$$

where I and I' are the original and the final intensities respectively, e is the base of Naperian logarithms, and x is the extinction-coefficient. This can be further simplified for the purposes of calculation thus:

$$\frac{I'}{I} = T = e^{-xd}$$

or

$$\text{Log } T = -xd \log e$$

where T is the transmission-coefficient. If I is taken as unity, of course the value of I' is numberically equal to the transmission factor. Aschkinass gives a table of extinction-coefficients for water for radiant energy of wave-lengths from 0.45 μ to 8.49 μ. It is thus possible to compute the transmission of the various eye-media for this range of wave-lengths. Aschkinass did this for the total eye but not for the various media. For the purpose of computation, thicknesses of water corresponding to the various eye-media were taken. These are reproduced in table 1.

TABLE I

Thickness of water corresponding to thicknesses of various eye-media

	Cm. of water
Cornea	0.06
Aqueous humor	0.34
Crystalline lens	0.42
Vitreous humor	1.46
Total depth of eye	2.28

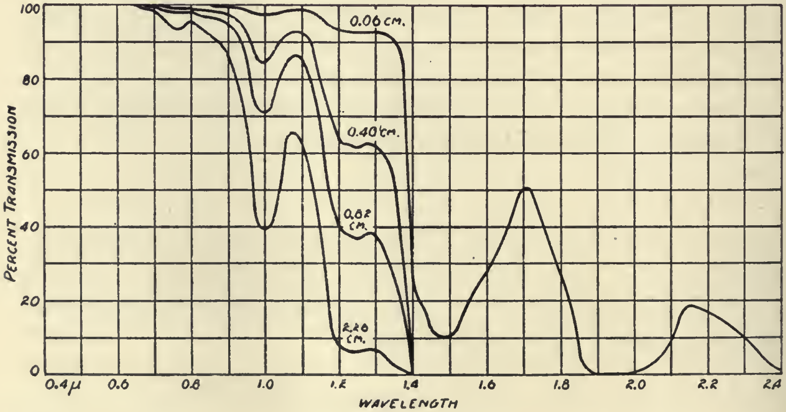

Figure 1. Transmission of various layers of water corresponding to the eye media.

Spectral transmission-curves were initially computed for four thicknesses of water, namely, 0.06 cm., 0.4 cm., 0.82 cm., and 2.28 cm. The first thickness corresponded to the cornea, the next to the cornea plus the aqueous humor, and so on. Obviously, the amount of energy absorbed in the aqueous humor, for example, is readily found by obtaining the absorption of the first two thicknesses and taking their difference. This was the general procedure. The spectral transmission curves of the four thicknesses of water are shown in figure 1.

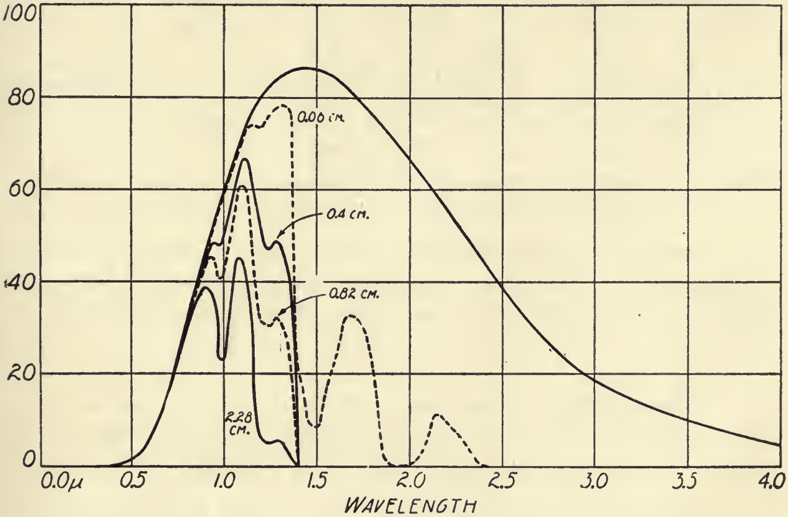

Figure 2. Spectral distribution of radiant energy from a 4-watt-per-candle carbon lamp through various layers of water.

The next point of interest was to apply these transmission-curves to the curves representing the spectral energy-distribution of black-bodies at various temperatures and also to those of various illuminants. This was done by multiplying the ordinates of the spectral energy-curves by the corresponding transmission-factors. Figures 2 and 3 show the results of this process with the spectral energy-curves of a 4-watt-per-candle carbon incandescent lamp and that of a

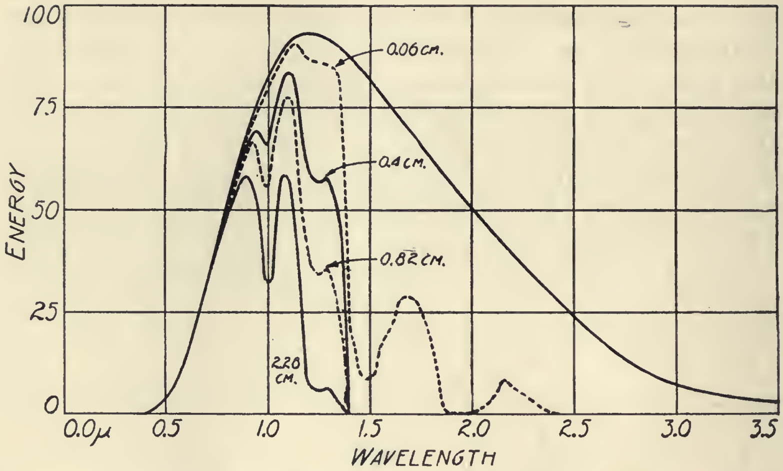

Figure 3. Spectral transmission of radiant energy from a tungsten lamp (7.9 lumens per watt) through various layers of water.

1.25-watt-per-candle tungsten lamp (7.9 lumens per watt) respectively. The numbers on the curves represent the thickness of water. For example, the percentage of total

TABLE 2

Percentage of radiant energy absorbed in the eye-media

Source	Percentage of Total Energy Absorbed in							
	Water of Depth				Cornea	Aqueous humor	Lens	Vitreous humor
	0.06 cm.	0.4 cm.	0.82 cm.	2.28 cm.				
Black body at 2000° absolute	68.8	80.6	83.8	89.7	68.8	11.8	3.2	5.9
Black body at 2500° absolute	51.7	63.3	68.3	76.7	51.7	11.6	5.0	8.4
Black body at 3000° absolute	38.5	49.8	55.7	65.1	38.5	11.3	5.9	9.4
Black body at 4000° absolute	22.8	31.7	37.2	45.9	22.8	8.9	5.5	8.7
Black body at 5000° absolute	13.0	19.6	23.4	30.4	13.0	6.7	3.8	7.0
4-w. p. c. treated carbon lamp	64.1	77.3	81.0	87.9	64.1	13.2	3.7	6.9
1.25-w. p. c. tungsten lamp	50.4	64.5	70.5	80.0	50.4	14.1	6.0	9.5

energy radiated from the carbon lamp which is transmitted by the cornea is found by obtaining the ratio of the area under this spectral transmission-curve (0.06 cm.) to the total area under the energy-distribution curve. The difference between this and unity gives the absorption of the cornea. The same process with the curve, 0.4 cm., gives the percentage of energy transmitted by the cornea and aqueous humor.

Obviously, the difference between the two transmission-factors gives the percentage of total energy absorbed in the aqueous humor, and so on. These percentages are found in table 2 and plotted in figures 4 or 6 for black-bodies at temperatures ranging from approximately 2000 to 5000 degrees absolute. At temperatures above 5000 degrees, the ultra-violet energy becomes appreciable, so no computations are given for higher temperatures. The curves would rise again for temperatures beyond 5000 degrees absolute. The energy of shorter wave-length than 0.35 μ radiated from a black-body at 5000 degrees absolute was found to be 3.8 per cent. of the total energy.

Though the eye-media are found to transmit the visible and infra-red rays in the same manner as water, this is not true for ultra-violet radiation. Water is transparent to short-wave radiation far into the extreme ultra-violet. In fact, no noticeable absorption was found for any of the ultra-violet radiation from the quartz mercury arc. It has been concluded by some that near ultra-violet radiation is chiefly absorbed in the eyelens owing to the fact that it strongly fluoresces under the influence of these rays. This conclusion has been strongly confirmed by spectro-photographic evidence. However, for black-body temperatures below 5000° absolute the ultra-violet rays need not be considered from the standpoint of the temperature effects due to absorption of this energy. In figure 4 are plotted the percentages of total black-body radiant energy absorbed by the various eye-media. It will be noted that for the cornea these percentages rapidly decrease with increase of temperature of the source, but much less rapidly for the aqueous humor, while the percentages of absorbed energy are a maximum for the lens and vitreous humor at about 3500° absolute. (See table 2.) This would hardly be foreseen without computation.

TABLE 3

Absorption of radiant energy in watts per lumen in the eye-media

Source	Watts per Lumen Absorbed in							
	Water of Depth				Cornea	Aqueous humor	Lens	Vitreous humor
	0.06 cm.	0.4 cm.	1.82 cm.	2.28 cm.				
Black body at 2000° absolute	0.153	0.179	0.186	0.20	0.153	0.026	0.007	0.013
Black body at 2500° absolute	0.04	0.049	0.053	0.061	0.04	0.009	0.004	0.008
Black body at 3000° absolute	0.012	0.0156	0.0174	0.0202	0.012	0.0036	0.0018	0.0028
Black body at 4000° absolute	0.0035	0.0049	0.0057	0.0071	0.0035	0.0014	0.0008	0.0014
Black body at 5000° absolute	0.0015	0.0023	0.0027	0.0035	0.0015	0.0008	0.0004	0.0008
4-w. p. c. treated carbon lamp	0.247	0.297	0.312	0.338	0.247	0.05	0.0015	0.026
1.25-w. p. c. tungsten lamp	0.064	0.082	0.089	0.101	0.064	0.018	0.007	0.012

It is seen that most of the energy is absorbed in the outer portion of the eye. In reality, this absorption rapidly decreases as the depth of the absorbing layer increases. This, of course, is to be expected from the exponential character of the foregoing equation relating thicknesses of the eye-media with the transmission-factors.

So far only percentages of energy absorbed have been considered. However, it is important to reduce the data to a common basis, that is, to find the actual watts absorbed per lumen. This was readily done by combining the foregoing percentages with the lumens per watt of the various sources. In figure 6 are plotted the values of watts per lumen for the black-bodies at various temperatures. Multiplying these values by the corresponding values from the

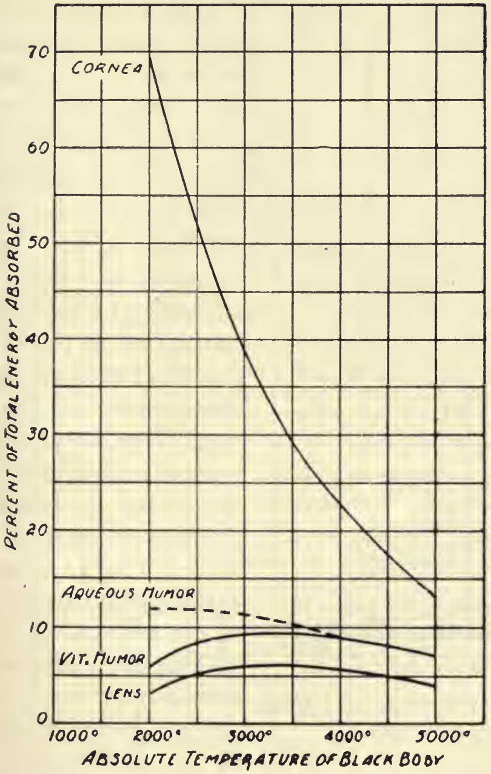

Figure 4. Percentage of total radiant energy absorbed in various eye media.

curves in figure 4, the actual watts absorbed per lumen are found in each case. These values are presented in table 3 and are plotted in figure 5. Curve *a* represents the absorption by the total eye (2.28 cm. of water); curve *b*, that by the cornea. Curves *c*, *d*, and *e* represent, respectively, the absorption by the aqueous humor, lens and vitreous humor. These curves indicate the actual power absorbed in the eye-media per lumen of light flux in the entering beam. The computations take into consideration only a beam of light of such dimensions that it enters the pupil; however, the exterior portions of the eye must absorb much energy in rays which could not possibly enter the pupillary aperture. The cornea and aqueous humor, besides absorbing most of the energy in the useful beam, no doubt absorb a great deal more energy.

It is thus seen that the outer layer of the cornea absorbs a large portion of the energy which is not active in producing the sensation of light, and, as is to be expected, the absorbed

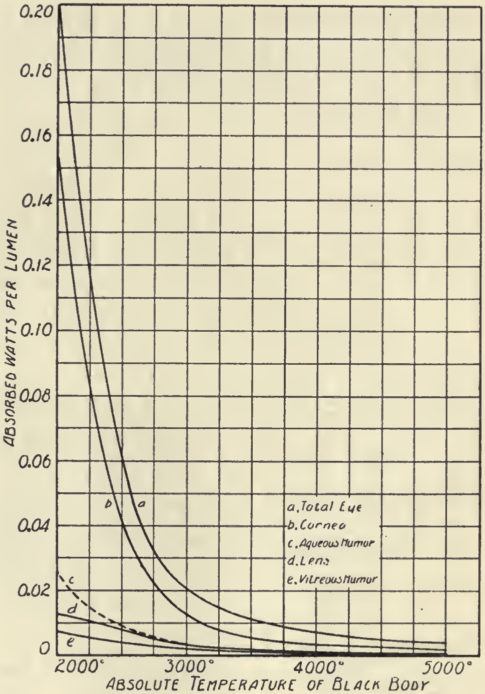

Figure 5. Watts absorbed in eye media per lumen in usual percentage of light.

energy per lumen of light flux incident upon the retina rapidly decreases with increase of temperature of the source. There would be an increase again for temperatures higher than about 5000° absolute due to the increasing amount of short-wave radiation. This, however, is not of interest here, because a large amount of the short-wave radiation would not be tolerated on account of its destructive effect. It will be noted that about thirty times as much energy is absorbed in the total eye per lumen of tungsten light as per lumen of light from a black-body at 5000° absolute. This same ratio would hold approximately for sunlight if it were not for the moisture in the atmosphere which absorbs much of the infra-red rays before they reach the earth and therefore the eye. This is perhaps fortunate considering the enormously greater intensities of illumination encountered in daylight. For instance, according to F. E. Fowle(8), the amount of precipitable water existing in the form of water-vapor between the top of Mount Wilson and the outer limits of our atmosphere during fair weather from June to November,

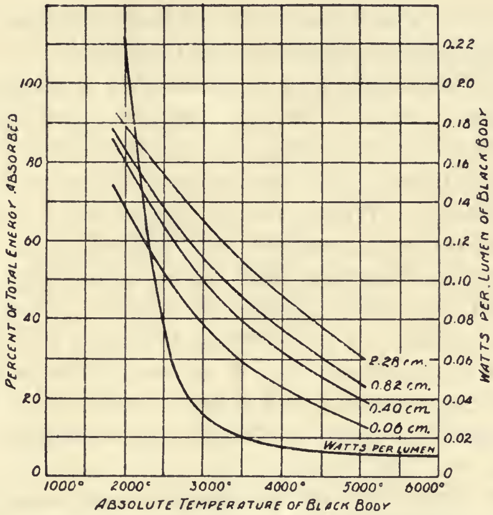

Figure 6. Percentage of total radiated energy absorbed in various layers of water.

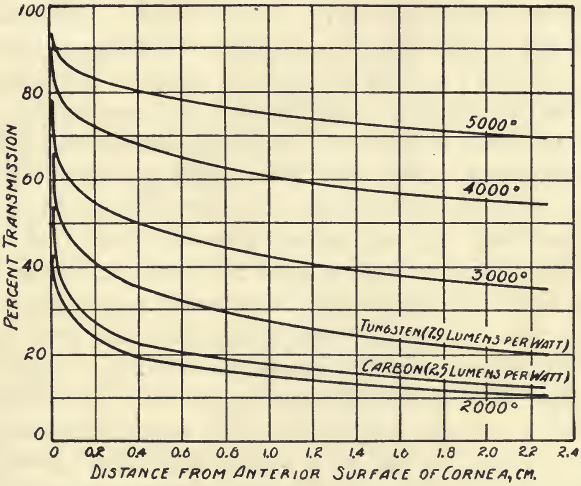

Figure 7. Transmission of various depths of the eye for the radiation from different sources.

1910 and 1911, was found to vary from 0.2 cm. to 2.8 cm. The average quantity present was 0.69 cm.

Another point worthy of consideration is the energy-density at various points in the eye along the optical path. Obviously, owing to the optical system through which the radiant energy passes, the energy-density varies in different parts of the eye. Where the energy is more concentrated the more serious effects might be expected.

Utilizing the foregoing and some additional data, the transmission of various depths of the eye (measured from the anterior surface of the cornea) is readily obtained. The spectral transmission-curves for radiation from a black-body at various temperatures and from a carbon and a tungsten lamp are shown in figure 7. Neglecting atmospheric absorption, which will be discussed later, the radiation from the sun can be assumed, for comparision purposes, to be approximately similar to that of a black-body at 5000° absolute. In order to obtain an idea of the energy-density in various parts of a beam of light passing through the eye, it is necessary to determine the path of the beam. Obviously, the path of the useful beam is slightly different as the eye is accommodated for near or distant vision. Data regarding the refractive indices, thicknesses and curvatures of the various surfaces of the eye-media as determined by Helmholtz were used. Only the beam that enters the pupillary aperture (in this case assumed to be 5.8 mm. in diameter) was considered. Computations give the paths for near and distant vision for a small object as shown in figure 8. The cross-section is considered circular as determined by the pupillary aperture. An image 0.01 mm. in diameter upon the retina would normally be formed by a circular disk 10 mm. in diameter viewed at a distance of about 15.5 meters. The refraction from the cornea into the aqueous humor is disregarded, owing to the very small difference between their refractive indices; that is, for the purpose of computation, the aqueous humor is considered as extending to the anterior surface of the cornea. The thickness of the cornea is shown to scale by the dash line drawn parallel to its anterior surface. The eye becomes shorter and the lens thicker when accommodated for near vision.

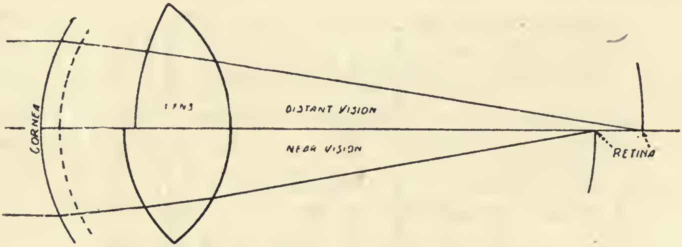

Figure 8. Path of light in the eye (small object).

The mean energy-density in various vertical layers of the eye-media under the above conditions is shown in figure 9. Curve *A* represents the relative energy-density in various parts of the beam if there were no absorption of energy by the eye-media. If the small disc be diffusely and totally reflecting and be illuminated by radiation from a black-body at 5000° absolute, the mean energy-density in various parts of the path of the beam is represented by curve *B* after allowing for absorption. Curve *C* represents the conditions when the illuminant is a vacuum tungsten lamp operating at 7.9 lumens per watt. It is seen, as might be expected, that the mean energy-density becomes relatively high near the retina. There is quite a uniform mean energy-density, however, for more than half of the distance of the path in the eye. This is due to the fact that the absorption of energy in the eye-media approximately overcomes the concentrating effect of refraction. In the case of curve *C* this absorption more than overcomes any concentrating action for one-half the distance. In order to compare curves *B* and *C* on a basis of mean energy-density per lumen, the ordinates of curve *C* must be multiplied by a factor approximately equal to thirty. In other words, the energy-density is about the same for a beam of tungsten radiation (7.9 lumens per watt) containing one unit of light flux as for a beam of radiation (of the same area of cross-section) from a black-body at 5000° absolute containing about thirty units of light flux. The energy-density curves are practically the same for near vision as for distant vision, and hence they have not been plotted.

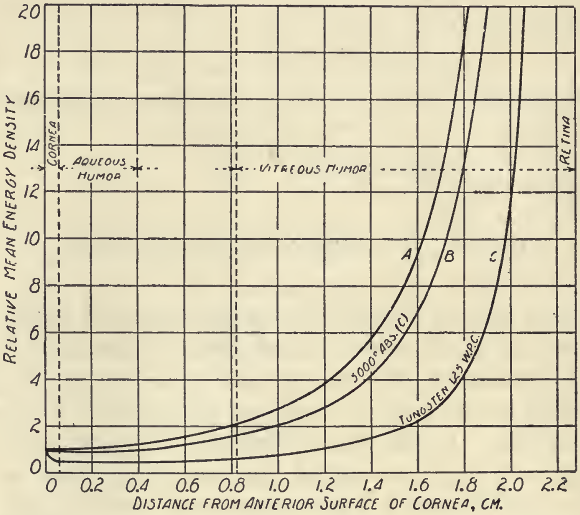

Figure 9. Energy-density in the useful beams of light from a small source (distant vision).

Before discussing the foregoing further, it is of interest to consider the other extreme case—namely, when the object subtends a large angle. The entire visual field subtends approximately a solid angle of 120°. The useful beam of radiation included within a solid angle of 120° at the eye is shown by the full lines in figure 10, when the eye is accommodated for a reasonably near vision. If the object that is being viewed be illuminated with the same density of radiation of the same spectral character as the object considered in figure 8, it is obvious that the brightness of the retinal image will be the same and a much greater amount of energy will pass through the pupillary aperture. In other words, the energy-density at the retina will be the same in the two cases, but the energy-density in the lens and anterior section of the eye will be many times greater in the case of the extended source. The ratio of the energy-densities in the plane occupied by the pupillary aperture will be approximately equal to the ratio of the solid angles subtended by the sources. In the two cases considered, when the brightnesses of the retinal images are equal, the energy-density in the pupillary plane for the case of the extended source is several million times greater than in the case of the small source. This is shown diagrammatically in figure 11 for equal energy-densities at the retina—that is, for equal brightnesses of the retinal images. Curve *D* represents the condition for the extended source and curve *E* for the small source.

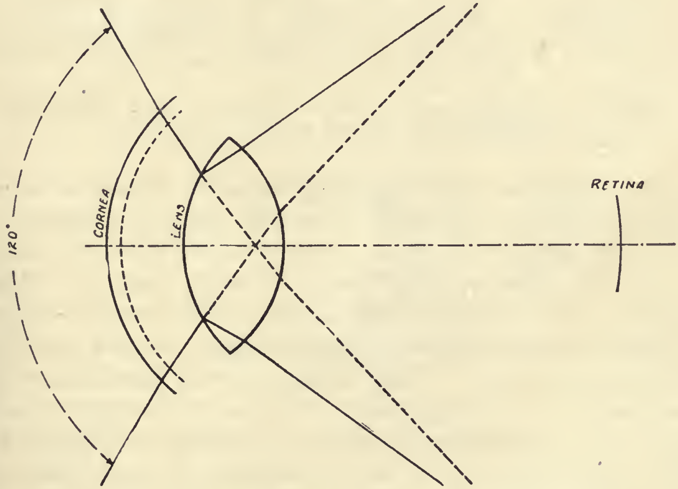

Figure 10. Path of light in the eye (extended object).

The foregoing conditions are of importance in many cases of vision if eye-fatigue or cataract is to be attributed to the absorption of energy. For instance, a small area of molten glass or metal may appear quite harmless. A larger area of equal brightness should appear equally harmless, but, as is evident from the foregoing, the actual energy-density in various parts of the beam would be far different in the two cases. In the case of a large area the energy-density in the lens would be many times greater than in the case of the small area. In ordinary vision there are many cases of extended areas of comparatively high brightness, such as a snow field, a desert, the sky, the wall of a room, and pavements.

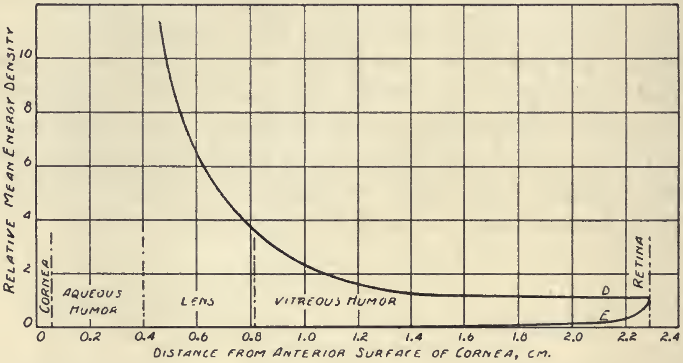

Figure 11. Energy-density in the useful beams of light from sources subtending large, D, and small, E, solid angles.

It is of interest to consider the possible effect of sunlight (radiation approximately like that presented or a black-body at 5000° absolute), but in doing so allowance must be made for the absorption of radiant energy by the water-vapor in the atmosphere. It has been observed that water-vapor is somewhat more transparent to the sun's radiation than is water in the liquid state. Assuming that the absorption of the water-vapor existing in the atmosphere is equivalent to a layer of the liquid 1.5 cm. in thickness, and with due consideration of the relative luminous efficiencies of a black-body at the apparent temperature of the sun and of the tungsten lamp, it is found that approximately a hundred times as much energy is absorbed by the eye per lumen of tungsten light as per lumen of sunlight. But it is not uncommon to find sunlight intensities far greater than a hundred times that encountered with artificial light under working conditions. In fact, the ratio of actual working intensities is often greater than 1000 to 1. This indicates that eye-fatigue and cataract should be quite noticeable under natural lighting conditions if they can be attributed to an energy effect. In fact, cataract is quite prevalent in India, but in this case, according to the work of Burge (4), the cause might be traced to an accumulation in the liquids of the body of something which so modifies the lens protein that energy of certain short wave-lengths can precipitate it, thereby causing an opacity.

To summarize: It is shown that when viewing luminous objects of small area (subtending a small solid angle) there is no serious concentration of energy in the eye-media until the retina is approached. However, when viewing extended objects (large solid angle) there is a relatively much greater energy-density in the lens and anterior parts of the eye than in the posterior portions. When the retinal images are of the same brightness, there will be a very much greater energy-density in the lens when viewing an object subtending a large solid angle than when the object subtends a small angle if the spectral character of the illuminant and the intensity of the illumination are the same. This indicates that large sources of radiation of a relatively low visual brightness might be effective in forming cataract or causing eye-fatigue if the "absorption-of-energy theory" is correct. In fact, if the deterioration of the lens is due to ultra-violet rays, the latter might be present in such small amounts as to appear harmless, but when it is recalled that the energy-density in the lens is very high when viewing extended objects, such as the sky, pavements, surfaces of molten glass, metal, etc., it appears to be possible that the ultra-violet rays still might be present in sufficient amount to do damage. From this standpoint sunlight, owing to the greater intensities encountered, appears to be probably as effective in producing cataract and eye-fatigue as ordinary artificial illuminants and some industrial processes, even after allowing for the higher luminous efficiency of the former and the absorption of energy by the water-vapor present in the atmosphere.

It is not claimed that the data in this paper settle the question of the influence of energy absorption in the eye-media. The object has been to show in what relative quantities the energy is absorbed in the various parts of the eye and also the energy-density in the path of the useful beam of radiation in order that those interested in eye-fatigue and cataract might have these quantitative data available.

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The Enigma of Color Vision

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IV

IF we trace the visual response arc backwards from the ultimate cortical area towards the retina the question immediately arises as to the manner in which the several components of the visual process are represented in the nerve conduction at various neural levels. The facts of three-color mixture, and the arguments with which the Young-Helmholtz theory has made us familiar, indicate that between the ultimate cerebral region and the retina this nerve conduction must involve at least three independent variables and that three are sufficient. *A priori* there are many different ways in which we can conceive the mechanism of this triplex conduction. Helmholtz assumed that there were three different kinds of nerve fibres and receptors in the retino-neural mechanism. Some later thinkers, abandoning the three-fibre theory, have imagined a threefold qualitative differentiation of the nerve currents passing along a single nerve fibre.

Recent discoveries in nerve physiology make the latter type of explanation even more difficult than it was at an earlier date, and it has never been very plausible. Prominent among these discoveries is the demonstration of the so-called "all or none" principle for the response of nervous tissue. It appears from the researches of Adrian and Lucas that the impulse which passes along a nerve fibre is incapable of quantitative variation, being fixed in magnitude by the inherent properties of the fibre. Gradations in muscular activity under the control of motor nerves are to be explained primarily in terms of variations in the number of nerve fibres in the nerve in question which are simultaneously in action. However, a further possible basis of gradations can exist in the *frequency* of the impulses, reaching the muscle along any given fibre, since the nerve current is intermittent or pulsatory in character and the individual pulses may be densely or sparsely distributed. In the case of visual sensation it is impossible to explain gradations of intensity or luminosity on the basis of the number of fibres simultaneously in action, since the number of fibres is reserved to determine our recognition of the *area* of the retina which is stimulated. It appears to be necessary, therefore, to account for the transmission to the brain of variations in intensity of stimulation of the retina by means of the conception of nerve impulse frequency, a weak stimulus sending fewer pulses per second along the optic nerve fibres than a stronger stimulus.

Recent investigations of my own appear to demonstrate the actual operation of the "all or none" principle in the optic nerve fibres, so that it is impossible to escape from the implications of this principle for vision by supposing it to be inapplicable to sensory nerves. There is an easily demonstrable entoptic phenomenon, first described by Purkinje, which seemingly depends upon stimulation of certain retinal receptors by the nerve currents generated in the conducting fibres of the retina as a result of stimulation of other receptors. The apparent brightness of the effect produced by this secondary excitation ought to be indicative of the intensity of the retinal nerve currents, and I have found by measurements of this brightness that it is substantially independent of the intensity of the stimulus which is initially applied to the retina. In other words, the nerve currents set up in the retinal and optic nerve fibres are independent in amplitude of the intensity of the stimulus which arouses them. But these currents must have some variable characteristic which represents the intensity of the stimulus, and apparently the frequency of the component impulses is the only plausible factor which can subserve this function.

The view that the intensity variable in the optic nerve currents is the frequency of the individual nerve impulses is obviously inconsistent with the assumptions of certain visual theories which have accounted for the transmission of the qualitative or wave-length aspects of the stimulus to the brain by means of impulse frequency. These theories based on the analogy of the telephone—like the Rutherford theory of auditory response—have relied on variations in the amplitude of the nerve pulses to transmit the intensity factor. According to the "all or none" principle, variations in the amplitude are impossible. The telephone theory of visual response is moreover inadmissible for another reason which has not in general been recognized by critics of this theory. This reason lies in the relation between the extremely high frequency or small wave-length of the radiation which stimulates the retina and the very low velocity of the nerve impulse as compared with the velocity of propagation of the radiation. This relationship demands that a telephonic representation of a light wave in the nerve current should be composed of waves whose lengths are far smaller than the diameter of an electron. Such a demand obviously reduces the theory to an absurdity, since the only manner in which these waves could be formed would be in terms of some sort of displacement pattern of the component particles of the nerve tissue, these being thousands of times larger than the required wave-lengths.

The view that the luminosity of visual sensation is mediated in the optic nerve currents by the *frequency* or density of quantal impulses is apparently the most plausible assumption which can at present be suggested. If the visual currents are actually quantal, or follow the "all or none" principle, they must have *some* frequency in order to exist at all, and this frequency will presumably be variable. What is more to be expected than that such variation should form the basis for the transmission to the brain of the most primitive characteristic of the visual stimulus, its intensity? We are certain that brightness vision precedes chromatic or complete color vision in evolution, and it is to be supposed that the forms of sensation first developed will have the simplest mechanisms. In another paper I have outlined a mechanism by which differing degrees of chemical excitation of the retinal receptors can be translated into corresponding nerve impulse frequencies.

Evidence that the visual process actually is of a pulsatory nature appears in the phenomenon of "Charpentier's bands," in which a single, moving strip of light against a black background is seen to leave behind it a train of alternate bright and dark bands. The stimulus, itself, has no such discontinuity which is a product of the response of the optic apparatus. The number of these bands observable in a given space—corresponding with the frequency of the pulses—increases with the intensity or brightness of the stimulus and, for ordinary intensities, represents a frequency of about forty a second; a plausible value for a nerve current. That there are difficulties in such an interpretation of Charpentier's bands, however, I freely admit. In the first place, the bands do not appear to be all of the same brightness, the leading one being the most luminous, this fact being out of harmony with the "all or none" principle. Secondly, the individual bands, themselves, possess the characteristic of luminosity, so that fundamentally luminosity would have to rest upon some attribute of the single nerve pulse and not upon abstract frequency. The frequency would only determine the degree of summation of successively delivered quantities of this attribute in the brain centers. If the leading band represents a single pulse it is difficult to understand how succeeding bands can exhibit a constantly decreasing brilliancy.

If brightness perception depends upon the frequency of the optic impulses, there should theoretically be an intensity so high that successive impulses will interfere by treading upon each other's heels. This would result in a progressive decrease in the luminosity produced by a unit increment of stimulus intensity (as each pulse fell more and more into the "relative refractory phase" of its predecessor)and finally in the complete abolition of brightness vision (with the impingement of an excitation upon the "absolute refractory phase" of its predecessor). Whether these considerations have any connection with Fechner's law for visual intensities, and with the blinding effects of very high degrees of stimulation is a question which I shall not here attempt to decide. Fechner's principle certainly cannot depend upon these relationships exclusively, since it involves "diminishing returns" at all levels of intensity, while the nerve processes would be operative only above a certain critical value. Moreover, below this value, we should expect a law opposed to that of Fechner, since the refractory phase which follows nervous excitation is itself followed by a phase of *hyper*-excitability.

One very interesting fact of vision which occurs to me as being explicable on the assumption that luminosity is represented by nerve impulse frequency, is the failure of brightnesses presented simultaneously to the two eyes to summate binocularly. This result would be obtained if the frequencies in the two optic paths were exactly "in step" as they arrived at the centers, the combined frequency thus being the same as that of the individual components, and the "all or none" action of the centers, themselves, preventing any increase in the magnitude of the unit pulses. When the brightnesses given to the two eyes were not equal, we should expect the higher of the two frequencies to predominate, but there would also be a certain amount of interference, so that the fused sensation would have an intermediate value, as in Fechner's paradox.

The idea of impulse frequency as the basis of luminosity vision provides us with a rationale of the nervous mechanism in achromatic sight, such as that of the retinal rod system or of the totally color-blind, but it leads us into serious difficulties when we go on to consider the probable basis of complete color perception. At first thought, it seems as if the "all or none" principle ruled out the possibility of more than one type of variation in a single nerve current. If luminosity depends upon frequency, upon what can hue and saturation depend? The single nerve impulse is monodimensional, while normal vision has been clearly demonstrated to be tri-dimensional. We shall return to this problem shortly.

V

The relations between the chromatic and the achromatic aspects of cone vision are, in general, very puzzling. The majority of luminosity effects are, at least to the first order of approximation, independent of hue and saturation. In addition to achromatic acuity, already considered, this is true of the temporal laws of luminosity minuthesis or "fatigue," the action time, critical flicker frequency, luminosity contrast effects, the relative brightness threshold, and the summation of brightnesses. All of these effects have "second order" dependencies upon color, but these are often explicable on a basis which makes the linkage between the chromatic and achromatic processes rather remote, as for example in the influence of the chromatic aberration of the eye upon acuity. The primary facts indicate that hue and saturation enter in only a very minor way into the laws which govern luminosity, and thus suggest the physiological separateness of the mechanisms underlying chromatic and achromatic vision, even in the cone system. This is in harmony with the expectations based upon the precedence of luminosity vision over complete color vision, in the phylogenetic series, and with the facts which show that chromatic sensibility can disappear without influencing achromatic sensibility.

Quite contrary to the views just expressed are the assumptions employed by Ives, Abney, and others in stating the results of three-color mixture equations in terms of luminosity. These writers regard luminosity virtually as an aspect of the chromatic valence of a stimulus or excitation. There can be no doubt that the luminosity of a mixed color is the sum of the luminosities of the components of the mixture, and also that every color must have a luminosity value in order to exist. Each of the spectral colors, moreover, has under normal conditions a luminosity which is strictly proportional to its chromatic valence. It does not follow from these facts, however, that units of luminosity and "color sensation" are interchangeable. The luminosity may merely be a proportional accompaniment of the chromatic value of the sensation, and not an integral attribute of the latter. The amount of luminosity accompanying a single chromatic unit of any spectral hue would depend upon the position of this hue relative to the visibility curve, and upon the inherent saturation of the hue.

That luminosity and chromatic value are actually independent aspects of the physiological processes underlying visual sensation is indicated by the radical differences in the proportionality constants relating these two factors for different spectral colors. Abney finds that when spectral red, green, and blue are mixed to form white, the proportions in terms of luminosity are 450:192:2.53, respectively. In other words, the saturation per unit luminosity of the green is more than twice that of the red, while that of the blue is one hundred and eighty times the latter! The complementary of blue, yellow, has a very low saturation, even as a spectral color, and a still lower one when formed by the mixture of red and green, so that the quantity of blue required to neutralize it is naturally small. If the visibility curve, or spectral luminosity curve, is regarded as the sum of the three color sensation curves, it follows from the above considerations that the former depends almost wholly upon the red and green sensations, the influence of the blue being nearly negligible, while the contribution made by the green is much smaller than that due to the red. This certainly suggests that the expression of color sensation values in terms of luminosities is merely a convenience of measurement or computation, not the revelation of a fundamental identity.

The question as to the relation between luminosity and chromatic valence would appear to be capable of a crucial test by measurements upon visual fatigue, or minuthesis, produced by different colors. Suppose that a considerable luminosity minuthesis is brought about by a spectral red stimulus, will this minuthesis have the same or a different value for a green or blue stimulus? If the luminosity process is independent of hue and saturation, a decrease of fifty per cent. in the luminosity of the red, due to exposure of the retina to red, should also bring about just the same decrease in the luminosity of any other color, including white, with which the retina might be tested. On the other hand, if each color process carries with it its own specific luminosity value, fatigue by extreme spectral red might have very little effect upon the luminosity producing powers of blue, or *vice versa.* Another way of putting the question is to say that if the sensitivities to brightness and to specific colors are only parallel visual functions, not essentially linked, minuthesis due to chromatic stimuli will not alter the *shape* of the *visibility curve,* while if they are essentially linked, such an alteration will occur. Measurements by Abney and by Burch indicate that color fatigue does in fact modify the form of the visibility curve, and recently published investigations by Allen, using the flicker method, point in the same direction. However, I feel some doubt as to whether these investigators actually effected a separation of the pure luminosity aspects of the process from the chromatic aspects, since extremely careful tests of my own, made with a representative variety of spectral stimuli and repeatedly verified, have failed to show any consistent linkage of luminosity fatigue with the specific color used to produce it. Work is continuing on this problem in my laboratory.

The interpretation of experiments along the lines just considered is somewhat complicated by the probable truth that if there are three elementary color processes, all of them are excited to some extent by all of the spectral lights. The only plausible exception is that the extreme spectral red does not stimulate the blue sensation. The three color sensation curves have several times been worked out on the assumption that the extreme red excites only the red sensation, but this is inconsistent with the idea that yellow is due to the concomitant excitation of the red and green sensations, since the extreme spectral red is distinctly yellowish, and becomes much more so as a result of minuthesis for red. The simultaneous excitation of all three of the color processes produces white, so that even the pure spectral colors are subjectively more or less desaturated, this desaturation being at a maximum near the middle of the spectrum. According to Abney, there is about 69 per cent. of white in spectral green. I am at present endeavoring to determine this intrinsic desaturation of the spectral colors by a method based upon the flicker photometer. The distribution curve of the inherent white over the spectrum bears a suggestive resemblance in form to the visibility curve, but I am not at present prepared to insist on my previous interpretation of this resemblance along the lines of the Hering theory which tends to identify whiteness and brightness.

The idea that luminosity depends upon a single, unitary, process and not upon the sum of three processes, irregularly distributed in the spectrum, is suggested—although certainly not proved—by the great symmetry of the visibility curve. I believe that I was the first to show that when the empirical visibility curve is corrected for the selective absorption of the ocular media, the result is an almost perfectly symmetrical curve—representing the actual sensitivity of the retina—which fits a simple probability equation with a high degree of accuracy. Priest later showed that this symmetry became even more perfect when the curve was plotted with respect to frequency instead of wave-length, the former method being theoretically the more defensible. The remaining deviations from symmetry in the blue end of the spectrum can be accounted for by fluorescence, a phenomenon which we know to exist in the retina.

This extreme symmetry of the visibility curve seems to me to militate somewhat against chemical theories of the visual receptor process. Resonance curves, in general, are asymmetrical; and the same is true of absorption curves, which are probably particular examples of resonance curves. None of these curves fit the probability function. The three color processes have curves which more closely resemble curves of resonance or absorption than does that of the luminosity aspect of visual sensation. Why these three asymmetrical color curves should be so delicately adjusted to one another as to add to form the perfectly symmetrical visibility curve is a mystery, if it is true.

One of the most salient riddles of the visual process is the cancelling effect which different colors have upon one another. Red cancels green and produces yellow, while yellow cancels blue and generates white. Each color has its complementary in combination with which it yields white. These facts, of course, are all implicit in the three-color-mixture system, but this system does not explain either their mechanism or their function. Mrs. Ladd-Franklin has objected to an explanation of this process of "complementation" which I offered in my theory of vision already referred to, because the explanation in question is completely *ad hoc*. She finds this a conclusive reason for rejecting my view since, according to her belief, "complementation" has no biological function and is, indeed, detrimental to visual efficiency since it makes us incapable of discriminating between "red-greens," "blue-yellows," and other combinations, all of which happen to make white. Mrs. Ladd-Franklin, in this criticism, raises a very important question, the question as to whether "color cancellation" actually has a function, or whether it is a defect in the visual mechanism, a corollary of some feature of the mechanism established on different grounds of utility. Before we conclude hastily that "complementation" is without a function, we should consider carefully the actual function and practical operation of chromatic vision as a whole.

We should recognize in the first place that color vision was developed to deal not with homogeneous or spectral lights, but with very heterogeneous or mixed lights. There are practically no spectral colors in nature, and very few transmission colors (as of glasses or gelatine filters); nearly all of the colors of nature are produced by selective reflection and are physically very unsaturated. It is surprising how little the luminosity distributions of most of these colors differ from that for white. Moreover, their deviations from white are not of all conceivable sorts. The variety of colors obtainable among artificial dyes is certainly much greater than that of natural pigments, but dyes having certain absorptions are very rare. Almost all dyes transmit the extreme spectral red. I do not know of any dye which transmits only the spectral yellow, absorbing the extreme red and also the green, blue and violet. There is also, I believe, no dye which absorbs the spectral red strongly which does not also absorb blue or violet. In the world of dyes, the inability of the eye to distinguish between a pure yellow and a "minus blue" can do no harm, because only the latter exists. A careful examination of the colors of nature would probably show that selective transmissions or reflections corresponding with homogeneous complementary pairs—Mrs. Franklin's reddish-greens, bluish-yellows, etc.—seldom or never occur. Among dyes the nearest approximation to a reddish-green is a "minus yellow," which looks blue, and to a bluish-yellow is "minus green" which appears purple or magenta. A careful study of the relations between natural colors and the properties of the trichromatic color vision system would seem to be well worth while.

The function of chromatic vision in its natural operation is to detect deviations in the distribution of radiant energy over the spectrum, from a certain standard form of distribution; *viz.*, that of sunlight. The distribution in the solar spectrum is itself by no means uniform, yet it is the one which normally gives us the sensation which we call "white." This sensation not only indicates the null point of the color process, but it is probably the visual quality which obtained for all operative stimuli prior to the evolution of the chromatic system. This latter system must, then, have been designed to modify the character of the sensation in proportion as the spectral energy distribution of the stimulus *differed* from that of sunlight, and—so far as possible—in a characteristic manner for each specific and actually occurring deviation. The simplest mechanism for the accomplishment of this purpose would appear to be one in which separate processes are excited by different portions of the spectrum and these functions are so arranged as to neutralize one another when simultaneously aroused in proportions corresponding with solar energy distribution. The function of complementation would thus be to restore or to preserve primitive, achromatic, vision when no significant deviations in energy distribution from that of sunlight exist among the given visual stimuli. The process of color adaptation makes the achromatic null point of the chromatic system somewhat adjustable relative to the actual energy distribution, so that under artificial illumination, a light yellower or even bluer than sunlight may be taken as the standard. What the eye actually seeks to record is, of course, the selective reflection of the object, but it can do this only through the medium of the given illumination.

When we subject the mechanism of the eye to stimulation with mixtures of selected monochromatic radiations, we are doing something essentially unnatural, but the result should be, and is, predictable in terms of what more heterogeneous spectral distributions would bring about. Complementary spectral wave-lengths are wave-length pairs which excite the elementary color processes in the same proportion as does solar radiation, or "white light." The physical energy distribution is quite different, but the retinal result is the same. The additive mixture of natural, or pigment, complementaries, on the other hand—on account of their broad selective reflection or transmission bands—would in most cases closely approximate in actual energy distribution the distribution which is characteristic of solar radiation.

The specific brightnesses, or ratios of luminosity producing power to chromatic valence, of the different spectral colors undoubtedly depends upon the requirement that the solar distribution should cause them to cancel exactly and give white. The radical differences which exist between these ratios are partly referable to the positions of the complementary colors relative to the visibility curve, yellow for example having a high visibility while its complementary, blue, has a very low visibility. It is clear that this explanation is valid only on the assumption that the luminosity function is evolutionarily prior to the chromatic system, the latter being forced to adapt itself to the settled character of the former in a very awkward manner. This is the only view, however, which seems to me capable of accounting for the awkward relations which actually exist.

Apparently the idea of the establishment of the luminosity function—including the visibility curve—prior to the evolution of the chromatic system does not enable us to decide definitely whether this system involves a plain *addition* to the luminosity mechanism or whether it depends upon some sort of *differentiation* of the latter, as in the Ladd-Franklin theory. There can be no doubt that there is a mere differentiation of the ultimate *cerebral* process because of the form in which the chromatic mechanism manifests itself in consciousness, but this does not necessarily imply that the alteration in the retinal function is of the same sort.

VI

If we consider the chromatic function by itself, the evidence that it depends upon three selectively sensitive elementary mechanisms, the responses of which are approximately represented by the curves of König and Dieterici, Abney or Maxwell, is apparently very strong. It has never seemed to me, however, that the facts of three-color-mixture, taken by themselves, show any more than that *if* color vision depends upon a number of elementary processes, there must be *at least* three of these. There might be more than three although so far as we can see on the basis of meager data the larger number would be of no advantage. However, the three color curves receive independent verification along different lines, notably from the distribution of hue sensibility in the spectrum, which coincides with the resultant of the slopes of the chromatic curves at any wavelength; and also from the facts of pure chromatic minuthesis, which serve to identify the intersection points of the curves. The recent work of Allen in this latter field with the flicker method is particularly impressive.

The essential mystery of the nature of the mechanism, however, still remains unsolved; we certainly cannot rest content with an analysis of the color function in abstract units like the three "sensations" of the traditional theory. We must endeavor to penetrate the reality of the process and to find out exactly how the action of different wavelengths upon the retina varies, and how the results of this selective stimulation are propagated to the brain. The bare idea that the retinal selectivity depends upon the presence of three chemical substances—pigments—having specific absorption or actinicity curves corresponding with the three "sensations" furnishes only the most primitive materials for a satisfactory hypothesis. We have still to ask how the selective responses of these substances can influence the optic nerve currents and exactly what this influence is.

It has seemed to me possible that the consideration of the probable mechanism of neural conduction of the chromatic excitations in the light of the newly established "all or none" principle will provide us with a fresh means of investigating the chromatic mechanism, since this principle sets such definite restrictions with regard to the nature of the nerve process. We have already seen that in all probability luminosity is represented by the impulse frequency; but at least two and, possibly three, more variables are required to account for the facts of complete color vision. What can they be?

It is, of course, possible to explain the color-mixture facts if we suppose, with Helmholtz, that there are three different kinds of cones, which are selectively sensitive to different ranges of the spectrum, and that these cones have separate connections, or "private lines," to the brain. Helmholtz himself adhered to this possibility in the second edition of his *Physiological Optics*, but his followers, *e.g.*, von Kries, appear definitely to have given it up. The reasons which have led to the rejection of the "three fibre hypothesis" seem, on the surface, convincing, although I am not quite sure that a different interpretation of the facts may not be possible. If there were actually three species of cones, we might expect to find some evidence of this differentiation, histologically, but no such evidence has been educed. Moreover, on this assumption we should look for a kaleidoscopic twinkling of very minute points of white light, such as stars, as the images of these points fall upon differently sensitive cones. Donders believed that he had demonstrated this phenomenon, but his findings have been refuted by later investigations. Anyone can determine for himself that even the faintest of stars in the sky do not fluctuate chromatically in this way. Other facts which lead to the view that each foveal cone is sensitive to all of the colors, are the possibility of correctly perceiving the colors of stimuli which fall (theoretically) upon only a single cone, and the correspondence of visual acuity in the fovea with the dimensions of the individual receptor.

However, I am not wholly convinced that the facts above considered necessarily refute the three-fibre theory. It is certain that the cones of the central retina differ from those of the periphery, and hence they may differ among themselves. This difference does not need to be anatomical, but only chemical, to fulfill the required function. The failure of "white" point stimuli to fluctuate in color can be accounted for as follows: If there are three different, separately connected, species of receptors underlying color vision, it is certain that the chromatic deliverances of adjacent elements undergo fusion in the brain; otherwise we would see all "whites" as delicate mosaics of three colors. Recent investigations by Hartridge show clearly that such fusion actually occurs, even if the receptors are without selective chromatic sensitivity, for minute color patterns falling upon a considerable number of cones are perceived in their integral quality and not as mosaics. Moreover, the isolated stimulation of a single cone is probably mythical, in spite of its theoretical possibility. Fixation is always uncertain to an appreciable fraction of a visual degree, and its fluctuations undoubtedly involve the oscillation of a minute retinal image over a wide area of cones at a relatively high velocity, our perception of the point being the fused resultant of the successive stimulations of a large number of retinal elements. It is also a significant fact that a considerable intensity is required in order that minute stimuli should be correctly perceived as to color, and the aberrations of the refractive system of the eye cause a spreading of the rays derived from even the smallest of sources, which is appreciable at high intensities.

The accurate correspondence of the limit of visual acuity with the dimensions of the single retinal receptors would still be possible even if these receptors did not all mediate the same quality of sensation. Each receptor would still have a separate connection with the brain, and a brightness pattern of fine black and white lines (as in an acuity test-object) would not be perceived as a chromatic mosaic, on account of the fusion of adjacent chromatic effects. The brain, in other words, may very well be capable of handling the chromatic and the achromatic aspects of the situation independently, fusing the former, but not the latter. I admit, however, that there are difficulties in the way of this view on the usual assumption of three-color theorists that luminosity depends upon the sum of the component color excitations, since on this assumption the luminosity judgment would necessarily rest upon a summation of adjacent activities, and certain types of brightness patterns could not be distinguished from certain color distributions. However, this usual assumption does not seem to me to be inevitable or, as I have indicated above, even probable.

Measurements of visual acuity are always made with brightness patterns, and the result depends almost wholly upon the characteristics of the stimulus in regard to brightness alone. It rests upon the absolute brightness value, the brightness contrast, brightness gradient, etc., and is nearly independent of the given hue or saturation. Exception to this rule appears to be due to the chromatic aberration of the refractive system and not to the neural mechanism. So far as I know, no exact measurements are available of acuity for pure *chromatic* contrast patterns; *i.e.*, patterns in which the stimulus field is of uniform brightness all over, but locally differentiated in color. There is no doubt, however, from qualitative experiences, that chromatic acuity is far lower than brightness acuity, indicating an extensive fusion of adjacent chromatic responses, with practically no such fusion of luminosities. This suggests strongly that the medium of luminosity perception is distinct from that of color differentiation. We already have evidence from brain pathology that the cerebral mechanisms of these two functions are distinct from each other. I hope before long to have some actual experimental data on chromatic acuity.

On the supposition that the retinal cones are differentiated into three kinds we still have a large number of possibilities open to us with regard to their exact manner of functioning.

Does chromatic vision depend upon the simple identity of these lines of conduction or does it rest upon some differentiation of the activities in the several species of cones? If their neural processes are all alike, luminosity can depend purely upon the frequency of the impulses, and the chromatic values will be determined by the central mechanism of counteraction between the several systems, which selectively weights the frequencies of the respective currents for the purpose of neutralization under the condition of solar energy or luminosity distribution. It is probable, however, that the three species of conducting nerve fibres would differ functionally as well as in their connections; the individual impulses travelling along them might, for example, have different characteristic amplitudes, although obeying the "all or none" principle in any single type of fibre. The fact that there are significant differences in the thresholds for different colors used to produce the entoptic phenomenon to which I have previously alluded is in harmony with this last suggestion. These thresholds are measured in terms of the luminosity values of the various colors, and the fact that equal luminosities do not possess equal powers to generate the effect in question—which depends upon the restimulation of the retina by its own nerve currents—is indicative of some quantitative difference between the currents produced by a given luminosity in different colors.

Another interesting possibility is that phase, or phase differences, may be involved in the neural propagation of the visual qualities. It is certain that in the auditory sense, differences in phase between corresponding nerve impulses arriving at the brain centers from the two ears are the principal basis of our localization of the sound. In vision, localization rests upon other relationships, but the factor of phase may still play some important part since the facts in audition prove that the brain centers are capable of employing it as a datum. Given a uniform luminosity over a considerable visual area, color might be represented in the corresponding volley of nerve currents by particular relative displacements of the phases of adjacent impulse streams. Such a system would of course require that a number of contiguous conductors should coöperate if a color impression is to be recorded. The central mechanism might consist of a species of neuron forming synapses concomitantly with the required number of optic nerve fibres, combining their frequencies when they were out of phase to form a new characteristic frequency or impulse pattern. Achromatic sensation would rest upon the exact synchronism of adjacent impulses, while chromatic vision would depend upon characteristic deviations from this condition. The frequency of the impulses in any given conductor, or for the system as a whole, would obviously be variable independently of such phase differences so that luminosity and color would depend upon distinct attributes of the process.

A mechanism of this sort, however, would clearly make possible a confusion of color and luminosity under certain special conditions. At the boundaries between light and dark areas, for example, there would be a tendency in this direction, since here it would be impossible for adjacent impulse streams to synchronize; in continuous vision, however, there would also be no constant phase difference. In momentary vision we should expect colors to appear at the boundaries of achromatic contrast patterns, an expectation which is realized in Fechner's colors and allied phenomena.

When we endeavor to imagine a retinal receptor mechanism which would produce relative phase displacements of adjacent nerve impulses in response to specific chromatic stimuli, we find the task a rather difficult one. Phase differences might at first thought seem to be producible by differences in the exact position of the source of the impulses in the retinal layer. The length of the cones increases in proportion to their chromatic sensibility, and experiments recorded by König and Zumft indicate that the retinal layers which are sensitive to different colors of the spectrum by no means coincide. This specific localization might be due to the positions of specifically responsive substances within the cones, or to certain optical properties of the latter. The minute laminae into which the rods and cones split up transversely to their lengths seem nicely adjusted to produce optical interference effects within the body of the receptor cells, which would place the maxima and minima of intensity of different wave-lengths at different distances from the bases of the cells. However, when we calculate the probable lengths of the nerve impulse waves, we see that any differences in phase which could be introduced by changes in the locations of their sources within the minute lengths of the retinal cones would almost certainly be quite negligible. The available data on the duration of the nerve pulse and its rate of propagation indicate that its wave-length is of the order of magnitude of half a meter, while the rods and cones are measured in thousandths of a millimeter. The difference in phase between the retina and the brain itself is probably a small fraction of a single wave-length.

The researches of Ives seem to show that the excitations due to the various spectral colors rise and fall at different, characteristic, rates; or, in the terms of his mathematical theory, they have specific "diffusivities." These characteristics may eventually throw some light upon the actual chromatic mechanism, although at present I do not see how Ives' analogy between the visual process and one of diffusion or radiation can be transformed into an actual interpretation of the retino-neural process. I am also somewhat doubtful whether his results apply at all to an isolated functioning of the retinal cones, unmixed with rod process.

It is possible that careful investigations along lines suggested above will show conclusively that single foveal cones are capable by themselves of exercising all of the functions of trichromatic vision. In this case we shall be obliged to ponder long and deeply concerning the mechanism of the process. Changes in phase relative to some standard might still be invoked, provided an apparatus for the establishment and maintenance of the standard could be demonstrated. Phase could either be advanced or retarded; these two counter-effective variations, together with frequency, might provide the three variables required. Another possibility, of course, lies in the ideas of impulse patterns and group frequencies. The individual nerve pulses could conceivably be spaced in different characteristic ways to represent the various colors, luminosity still depending upon the total number of pulses arriving per unit of time. A stream of rapid impulses could be broken up by gaps of different sorts, these gaps only being detected by the central *color* receiving apparatus, which may be too lethargic (of too long a refractory period) to pick up the faster series which control luminosity perception. However, when we raise the question as to the retinal mechanism by which these effects are produced, we find ourselves again at a standstill.

If we endeavor to explain the transmission of chromatic impressions to the brain on a "telegraphic" basis, as just suggested, by various characteristic variations of the stream of pulses from uniform periodicity, it is possible that the phenomenon of "complementation" could be accounted for by the accidental neutralization of one such variation by another. Complementation would, on this theory, be a non-functional corollary of the mechanism of the visual impulse, the latter being restricted in its ability correctly to transmit the retinal impressions, by the narrowness of its channel. The complementary reaction in general suggests the relation between two conflicting nerve currents known as inhibition. Modern studies indicate that the inhibition of one current by another may be determined by the relative *frequencies* of the two in conjunction with the properties of synapses—or neural junction points—upon which they both impinge.

There are many conceptions and systems of relationships in modern neurology which seem of great promise as materials for the construction of visual theories. The "all or none" principle, with its implication that all nerve currents consist of series of pulses of fixed amplitude and definite frequency or pattern, lays a firm foundation for our thinking. Clear ideas are gradually developing of the nature and mechanism of the so-called "nerve centers," now mainly identified with the synapses. Many visual phenomena must depend upon the properties of the synaptic factors in the optic conduction paths. Sherrington's classical book on *The Integrative Action of the Nervous System* contains frequent comparisons between purely physiological reflex processes and the facts of vision. Thus, both of these functions are subject to fatigue or loss of specific sensitivity with constantly repeated or continued excitation. In vision, the evidence of such fatigue is the "negative after-image." However, there are also *positive* after-images, consisting in a continuance of the sensation after the stimulus has been removed. These find an analogue in reflex action in what is known as the "after-discharge." What Sherrington calls "immediate spinal induction" is suggestive of "irradiation" in vision, while "successive spinal induction" has features of resemblance to visual contrast effects.

VII

In the present paper, it has been my aim to discuss the problems of color vision mainly from the point of view of neurology, considering how the facts relate themselves to the principles of action of the nerve conductors and centers. The point of view most frequently adopted is that of the sense-organ or receptor process. In closing I wish to refer briefly to a few properties of the retinal rods and cones which must enter into the final solution of the enigma of vision.

One of the most astounding characteristics of the visual receiving apparatus is its ability to deal with a scale of radiation intensities ranging from quantities close to the smallest which are capable of physical existence to values a hundred million times as great. Recent measurements of the smallest amount of energy required for vision indicate that the retinal rods, in the state of full dark adaptation, are capable of responding sensibly to from ten to twenty *quanta* of radiation, the quantum being the ultimate physical atom of radiant energy. As this estimate refers to the amount of radiation striking the eye, it is probable that the actual quantity operative in the retinal cells is considerably less; it seems reasonable to suppose that some of the light striking the rod itself will be transmitted through its mass rather than absorbed. Thus if modern theories of radiation are correct, the retina is capable of dealing with almost any possible quantity of radiation, of the proper wave-length.

This extreme sensitiveness of the retina seems to me to throw doubt upon simple chemical theories of its operation. Ten radiation quanta could not possibly decompose more than ten chemical molecules, and this action—even in so small a body as the terminal segment of a rod-cell—would be so slight as to be inappreciable in any except the most highly sensitive physico-chemical system. If the action, however, were the production of ten molecules of a *catalyzer* or enzyme which then released a secondary chemical change which was far more massive, the final effect of the generation of a nerve current might become intelligible. Hecht has recently educed evidence that the initial process in the action of light upon the photo-receptors of certain molluscs is actually the production of a catalyzer. It is possible, then, that the visual purple is a zymogen—or pre-enzyme—which is "activated" by light.

Another puzzling feature of the retina is the fact that the cones, the receptors for color, are themselves quite colorless. Since the visibility curve for the cones has a sharp maximum in the yellow-green, it would seem inevitable that the cones should be more strongly absorptive for this than for other colors of the spectrum, and hence that they should be purple or magenta in hue. Possibly the failure of histologists to detect any coloration of the cones is attributable to weaknesses in their technique. If the chemical mechanism of the cones is the same as that of the rods, they would require less than one-thousandth as much pigment as the latter for their most sensitive functioning, since their thresholds are about a thousand times higher than those of the rods. On the other hand, it is conceivable that the cones contain a *mixture* of pigments—say of three, representing the three components of the Young-Helmholtz theory—the result to external observation being a gray. In this case, fatigue of the living retina with colored light should tint it with the same color as that of the light in question.

It seems improbable, on the whole, that the mechanism of the cones is essentially similar to that of the rods. Rod-vision sacrifices specific chromatic sensitivity for the attainment of extremely high general sensitivity. Chromatic sensibility, it would seem, imposes a mechanism which demands considerable energy for its operation. Several writers have recently suggested that the action of radiation on the visual cells is to be identified with that of the so-called "photo-electric effect," which consists in an ejection of electrons from a metallic or other surface under the influence of the radiation. It is practically certain that electrons are ejected—in the retina as elsewhere—but the actual question is whether the next step is a chemical change, an increased ionization—as suggested in my "photo-ionic" hypothesis—or possibly some direct action on the receptor cell membrane. It is a well-known fact that the incidence of light on the retina increases its electrical negativity, an effect which could be attributed to an emission of electrons or negative ions. The electrical forces of the light rays are perpendicular to the axes of the rods and cones, so that the long, cylindrical form of the latter is favorable to their maximal action. Another possibility is that the radiation acts directly upon the cell-membrane, changing its permeability and initiating an impulse in harmony with principles of nerve excitation which it is impossible to consider here in detail.

It is still possible, I believe, to arrive at some new and valuable ideas regarding the probable mechanism of color vision by further careful study of the receptors. Unfortunately, this study seems of late to have been little pursued experimentally, at least in relation to human vision. At first thought, it appears that the selectiveness of the retina must be due to some sort of resonance, and it is very easy to show that, in this case, the responding unit must be a chemical molecule. There is one theory at least, however —that of Darzens—which utilizes a different selective principle; namely, that of interference. He supposes that reflection within the receptors produces standing waves, the energy nodes or loops of which are situated at different positions for the various wave-lengths. In thinking along similar lines, it is interesting to note that the rods and cones are not only of high refractive index but are doubly refracting, so that the actual wave-lengths of radiation within their substance are considerably shorter than in air and, moreover, there must be two sets of these waves—of different corresponding lengths—one for the "ordinary" and the other for the "extraordinary" rays which accompany double refraction.

VIII

As stated at the outset, it is the purpose of the present paper to present some of the facts related to color vision as elements in a riddle or an enigma, rather than to develop any consistent theoretical explanation of these facts. Practically all of the possibilities which I have discussed are, at least in my own mind, in a very fluid condition. The actual task which we have before us in constructing a rationale of the data of physiological optics is a tremendous one, making more rigorous demands upon the intellect, I fear, than the formulation of certain far more cosmic theories, and one upon which our present, neat little academic explanations form only a burlesque.

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Editorials

Stereopsis as a Desirable Routine Test

DURING the past two or three years a rather extensive series of experiments has been carried out upon the matter of the ability of a normal pair of eyes to distinguish a depth distance. Pulfrich, James, Eaton, Howard, and Wells have contributed to the literature upon this subject. There is apparently quite uniform agreement that, while monocular judgments are valuable, the binocular parallactic angle is absolutely essential to any refinement of this faculty. Howard adopted a slight modification of the James apparatus and made exhaustive tests of the aviators at the medical research laboratories at Mineola. In a general way he concluded that individuals with normal eyes, of equal acuity and showing orthophoria, should possess a depth difference of about two centimeters at six meters, hence giving a parallactic angle of ten to eleven seconds at that distance. It was likewise found that errors of refraction, muscular imbalances and allied physiological factors caused a decrease in the ability to accurately judge distance. Furthermore, there are many with normal muscle balance and with acuities practically normal—either naturally or through correction—who do not possess the ability to form an ocular estimate of the relative distance of two objects in accordance with the average, or what we may call standard results.

The importance of the possession of normal judgment of depth difference on the part of aviators has been clearly and uncontrovertibly demonstrated. The work of Howard upon this point is most valuable. In an article appearing in the first number of the *Archives of Ophthalmology* for the year 1920, Dr. David Wells has called attention to the fact that it is very possible that chauffeurs, engineers, motormen and other vehicle drivers should be tested as to this matter of stereopsis. He says: "When the facts are known it is quite possible that visual tests will not stop with measuring the acuity of each eye and the color sense, but that a certain standard of stereopsis will be required."

In his paper on "Horopterscopic Vision" presented in this issue of this JOURNAL, Dr. Hazen calls attention to several aspects of binocular single vision and in particular discusses weaknesses in this function and the general effects to be expected. In the closing portion of his article he remarks: "The safety of the public conveyance depends largely upon this faculty being perfect in the motorist or engineer who guides them, yet not now tested by those who are supervising these public interests."

We believe that Dr. Wells and Dr. Hazen have touched upon an important point. In these days of the ever prevalent automobile and in these days when we pick up the Monday morning newspapers to read of the many Sunday accidents, we may well wonder whether or not all of these accidents are due to carelessness and recklessness. Possibly it is true that our laws and regulations need greater stringency in the matter of the qualifications of those who drive cars: it is certainly not sufficient that two or more persons swear that we are of good character and that we can drive a car for a few miles, start, stop, and reverse it, under conditions that call for no test of judgments of any character. Without doubt we need visual acuity and muscle tests as a part of an examination for a driver's license and in addition we need the test of stereopsis. The writer is positive, from some data very roughly gathered, that judgments of depth distance are very faulty in many cases tested and that, therefore, it is possible that drivers rush in, literally, "where angels fear to tread," and that lives are lost and cars are wrecked in many instances because of a faulty judgment in the ocular estimation of the relative distances of two objects. The apparatus of Cohen, as modified by Wells, permits of the getting of the depth difference and thereby the parallactic angle in a very few minutes' time.

Of course, it is obvious that the problem of distance between moving objects, especially objects on opposite sides of a highway and moving in opposite directions, involves the element of an estimation of time, for instance, as to when they will pass each other. But in the last analysis it is a question of judgment of distances in large measure and the sense of the time element involved is apparently dependent upon the matter of space judgments. But it appears at first glance as reasonably sound to believe that if tests of depth differences with stationary objects show a subnormal condition, these judgments of depth difference would be all the more uncertain if the objects were in motion.

At any rate, this subject is worthy of attention by all those interested in the practical applications of physiological optics.

A Sensitive Test for Determining Small Amounts of Astigmatism and the Principal Meridians

THE question has often been asked as to how one may accurately determine whether or not a small amount of regular astigmatism exists and, if such a condition is found to exist, how the proper axis of the correcting cylinder may be located. Until recently but little could be offered by way of an answer or even a suggestion. We are all aware of the difficulties of subjective findings. Various forms of type and other arbitrary test-objects suffer from the fact that the transition from one size to another is not gradual and that the element of recognition enters to assist the eye. Ives devised a simple apparatus in which the size of the detail of the test-object can be very slowly changed. By shifting the gratings into different positions and by observing the equality of appearance or disappearance of all limbs of the test-pattern or by determining the acuity in different meridians, considerable accuracy may be obtained in determining both the amount and the principal meridians of small astigmia.

Retinoscopic determinations in the hands of one conversant with these methods often clearly indicate small astigmatic errors, but no one we believe would claim an accuracy of more than five degrees in estimating the position of the correcting cylinders. And as to the accuracy of the determination relative to the amount of astigmatism we shall be satisfied by remarking that even the most skilled practitioners find it difficult to check within an eighth to a quarter diopter—a quarter diopter being the limit of difference, however, in skillful manipulation—in many cases. And again, when such cylindrical corrections have been objectively found, we often find that they are subjectively rejected as not being of as satisfactory a character as their omission or else no apparent improvement in acuity is forthcoming at the time of test. Subjects under examination give us answers of uncertain or variably interpretable meanings. Many have relegated to the scrap-heap the clock-dial or the fan test and have depended upon the ability to differentiate letters which might be easily confused. But we have in recent years found out that all letters used in our test types, although properly made as Snellen type subtending five-minute angles, are not equally readable by standard or normal eyes, for some letters of the same size may be read at greater distances than others. And the ophthalmometer has proven of little value to us in investigations upon small amounts of astigmatism. The cross cylinder test, to be sure, has many points in its favor. It is quite obvious, therefore, that unless some radical improvements can be devised and introduced into our clinics and offices, we can hope for no absolutely dependable returns from the various methods we have cited.

It has, therefore, been a source of considerable gratification to many of us that Dr. Ferree and Dr. Rand, working in the psychological laboratories of Bryn Mawr College on this and allied problems, have demonstrated that *illumination* can be used as the determining agent. The experimental device is extremely simple and is essentially a projection lantern of ordinary form with a Mazda lamp illuminating an aperture screened with ground glass and so arranged that an iris diaphragm enables the illumination contained within the light image thrown upon the letters on the chart to be varied at will. A scale attached to the iris diaphragm enables the illumination to be read in terms of meter-candles. Not only can the instrument be used for measuring the resolving power of the eye in any meridian desired and thereby determining the existence of and necessary correction for an astigmatic error, but it possesses other uses some of which are quite obvious. Amongst these may be mentioned: (1) a means of illuminating the Snellen type with a constant and known intensity of light—a very important point; (2) the testing of scotopic or twilight vision and the rate of scotopic adaptation, thus testing the light sense in so far as it affects the power to see clearly; (3) the testing of the light sense directly in terms of the amount of light required to arouse just noticeable sensation and (4) the testing of small errors of refraction by determining the minimum of illumination with great exactness. The tests for small amounts of astigmatism and the effects of shifting the axis of a correcting cylinder is obviously based upon the principle that if the eye has equal resolving power in all meridians the amount of light required to just discriminate the test-object will be the same in all meridians. If the resolving power is not the same, the amount of light required will be different in the different meridians. Experiments by Ferree and Rand indicate that in the case of an astigmatism produced by a quarter of a diopter cylinder there was an average of about one hundred per cent. more light required for the discrimination of the test-object in the worst as compared with the best meridian. With regard to the sensitivity of the apparatus for detecting small errors in the position of the correction for astigmatism, these investigators show that, in a case produced by a 0.75 diopter cylinder, a displacement of 5 degrees required about one hundred per cent. more light than the true placement, and a displacement of 10 degrees of something over one hundred and sixty per cent. more light. In working upon the matter of detecting errors in the amount of correction for an astigmatism it was found that an eighth diopter cylinder produced a measurable difference.

As Drs. Ferree and Rand point out in their articles, these experiments were carried on with astigmatic conditions artificially produced, hence it does not follow that the minimum amounts of light required for the true and false corrections would be identical with that which would be gotten with a natural astigmatism. Doubtless the astigmatic eye learns to compensate in part for its defect.

But in essentials and fundamental principles the writer believes that such tests as these will come to be a part of our clinical procedure. In testing for astigmatism, for example, it seems possible to very quickly use a properly constructed fan-chart and to determine which set of lines disappears first as the illumination is reduced or else, with a single set of three or four lines, the minimum illumination could be determined in various positions of these lines. Roughly then, the cylinder so placed as to give approximately equal resolving powers in all meridians would give an approximate correction and the niceties of the test as to the position and amount of the correcting cylinder could then be completed. The method appeals to the writer as being generally applicable to all astigmatic conditions, whether of large or small amounts and whether simple or compound, since every case, when wearing a final correction, would find itself in the category of the determination of the proper amount and position of the correcting cylinders. This subject is worthy of much experimentation, and it is to be hoped that these methods, or those which may be offshoots from them, will be perfected. Elsewhere, in this issue, are rather complete abstracts of the papers by Professor Ferree and Dr. Rand: we commend to all our readers a perusal of these abstracts as well as the original papers on this topic.

Horopterscopic Vision

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THE author of this paper has already written two papers for the *Archives of Ophthalmology*, in which he suggests the pathology of asthenopia as being in the muscular system of the eye; especially in the extrinsic muscles, which are the controlling apparatus of binocular vision. To this pathologic idea as set forth, he would now add a new view of this apparatus; that, together with the focal apparatus, it constitutes a *distinct function*, *which is our pilot for the guidance in safety of our person* in the walks of life, and presides over the activities of the industrial world; that to the capacity of the animal world to see monocularly, man has acquired this perfection of binocular vision.

Here is a perfected organism, found only in the human species, that presides over every motion, from the first awkward step in childhood, to the last handshake of the aged. It gives to the young the means of making life a joy; it provides skill for the middle-aged to gain a livelihood; it furnishes the elder the instrument to add to his knowledge.

The wonderful attribute of this function to measure space and converge on the infinitesimal is furnished with an apparatus to accomplish it, so exact and capable that, before we knew the function it controlled, we were awed at its mechanism and adaptation.

And, as I believe, this new conception of this apparatus promises not only greater insight for relief of asthenopia but it broadens the view of ophthalmology by considering this motor apparatus, at which we have tinkered so long, as belonging to an important function, calling for study of higher attributes, and a commensurate grade of professional service for its care; for apprehension of further necessities in this recondite and highly developed faculty will require acute observation, ingenuity, and perspecuity; the higher the grade of any function, and the more often it is called on, the more complications may be expected.

I have arrived at these conclusions from my study and treatment of over two hundred cases of pure "muscular asthenopia" during a period of twenty-five years. I treated these muscles wholly by orthoptic exercise, having invented an instrument, the *kratometer* (Fig. 1), with batteries adapted to the character of the different pairs, and learned to handle them in their idiosyncracies. My point of view then was that asthenopia was often from weakness of the muscles, and that discipline of them would restore them to do their work.

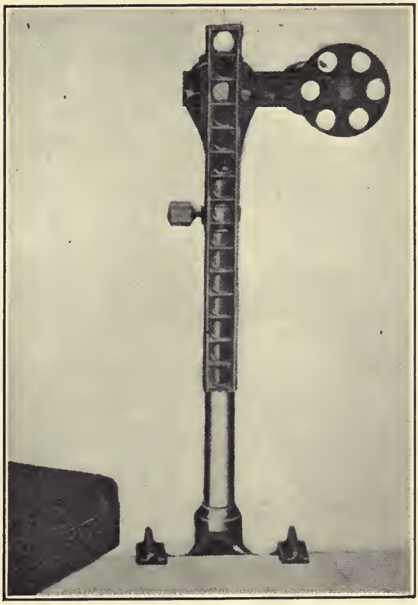

Fig. 1. The Hazen kratometer.

The response to this method was gratifying; the normal duction of the muscles was soon brought about, the eyes were always cleared of hyperemic conditions of any of the layers, if present; the nervous symptoms were dissipated, and all so quickly done, I often wondered what I had found.

It is only within the last two years I have been enabled to generalize this phenomena in the conception as above given; *viz.*, That asthenopia is the disorder of this function—a débris or poison, the product of inflammation and hyperemia in the tissues, that obstructs the motor movements, so that by the exercise of these muscles this débris is pumped into the circulation. All of which is the conviction of the writer.

The history of medicine gives no better example of arduous labor, of more painstaking investigation, or of a more extensive literature created, in the last fifty years, than that which encompasses but a fraction of a specialty, as does physiological optics in ophthalmology.

But there has not been that apprehension of the natural synthetic relation of this apparatus to the active affairs of everyday life, or to that of its disorders, with the many obstruse symptoms that have puzzled the neurologist who has so much to do with this function.

For the perturbations of these ocular orbs, the mechanical or dynamic method has been adopted; "imbalances," "torsions," and misfit muscles have been attacked with scissors and other means of the artificer and we have overlooked altogether the pathological conditions of this muscular system.

This pathological idea of débris, sepsis or unsanitary condition of the eye may not be found to be exactly correct, but it is a good working hypothesis.

In a high percentage of these disorders of the muscular system, there is associated with it inflammation of the tissues of the ball and lid. This is invariably cleared up in muscular exercise, suggesting the idea that as a sanitary measure the orthoptic treatment is a general hygienic measure of great possibility.

We have a word in the science of optics, which has been laboriously worked almost out of existence in defining it, but which we need not fear using in this connection. It is *horopter*. We will use it to describe the extent of the binocular field of vision, and leave out the intricate phenomena discovered within its bounds. The horopter is simply the space in which a person can maintain single vision (not doubled). When the head is fixed in the primary position, casting the look to the left as far as one can see singly, and then to the right, the lines that would describe these boundaries on the sides and all the space in front between the ground as floor, to infinity, together with the arch above, is the horopter of that position of the head.

The function of *ocular orientation* or binocular vision is performed within the horopter, and may be divided to distinctly describe it.

Orientation includes *projection* and *perspective*. *Subjective-orientation* is the relation of objects to ourselves, and *objective-orientation* is the relation of objects to each other. *Projection* has relation to the focal apparatus, the transparent media, the crystalline lens, the cornea and the regulation by the iris. The system of refraction and accommodation has the care of making definite and clear the object and the ease of its service. *Perspective* is binocular vision gotten by the extrinsic system of muscles and is governed by it. The anomalies of this apparatus are corrected by the administration to this muscular system. In the normal performance of these several acts, comprising orientation, one faculty on which but little is said in the description of binocular vision, is the *speed* with which the acts are performed. The muscles of the eye are the quickest muscles of the body. This apparatus will function forty times while the legs take one step.

When we consider the necessity of accuracy in focusing, the precision in adjustment of the eyeballs in fixing, the speed with which it is performed, and that the cerebrum depends upon it for judgment in coördination and equilibrium, and that so many hours it will perform its duties, and that a whole lifetime may render such service without breaking down, it deserves our adoration. Yet we are aware that from its extreme delicacy of construction and its severe requirements in the works of ambitious man, it needs the aid of science to keep it in repair and efficiency.

It is said that the lower animals have no conception of "space;" that they do not have convergence. It is very certain that none of the lower animals have the binocular vision of man, and we can easily believe that the industries in which man has of a necessity been employed is the environment which has brought about to so great perfection this function of binocular vision.

It is the observation of ocular practitioners that hypermetropia of the higher degrees are found in families of the illiterate, or those whose occupation has not required near vision; that they are unable to focus at the near point for long at a time. The same inability for near work may be said of the ocular muscles, weak convergence, of those who come from rural districts, whose work has been at arm's length or beyond for generations; they are unable to converge protractedly. The descendants of these people, from a desire to better their children's condition, send them to school. This new environment severely taxes their powers of convergence, and they often break down or find it too difficult to keep up in their classes in consequence. This is a very common experience.

The higher endowments of man are obtained by studiousness, industry, and assiduity; that means an intense requirement of this function of binocular vision, consequently we find troubles most frequently among the studious and persistent worker at the near point. Many "break down" in college and have to change their whole course of life. A common prescription for this kind of ailment is six months' rest. We have examples of this kind of invalids in every community who are laid upon the shelf and are so inventoried. The majority of these are unrecognized asthenopes and amenable to treatment.

In selection of employees for assignment to different requirements there has been no examination of this function, yet it plays an immense figure in efficiency and adaptation. The success or failure, or at least the ease of its performance, depends largely upon the healthfulness of this faculty; I believe as much as upon any other qualification usually investigated. The willing minds of a host of applicants go through experiences of change under this incubus, but they know not, nor does the glass fitter explain why "fate is so unkind." I believe that half of the industrial workers have more or less deficiency in this binocular apparatus which weakens or makes inefficient many of the other highly endowed attributes of the human race.

A one-eyed man, for instance, who has no power of measuring distance cannot successfully do carpenter work. He cannot with facility drive nails. A one-eyed man can superintend, if he has knowledge of the business. Other qualifications made good, he can make a solicitor, salesman, teacher. He should never drive a public conveyance in a thoroughfare.

It is obvious that the trapeze performer, the bareback rider, the tennis player, the ball player, the aviator, must have the faculty to perfection to excel in their calling.

The American people read much, and modern methods through invention, the service in the industries, give little variety of muscular play, and this function being the chief reliance for guidance, it is soon worn out. Until the symptoms of pain are developed, there is no recognition of the deficiency and generally no complaint is made.

Tests

We are wanting in tests of precision for this disability to enable us to recognize the deficiency in this apparatus without having to depend on the declarations detailed by the patient. We have the prism for the fusion power, and duction, in which it produces the effect on the periphery of the retina, of a moving object at the side of the direct gaze; and as we have fixed the standard of normal duction of the laterals at 50°, if the subject can fuse a succession of prisms aggregating 50° in twenty seconds, these converging muscles may be pronounced normal. The other pairs should perform the standard degree of each pair in the same time.

Hering's *drop-test* as figured in the textbooks is very crude, and as the principal valuable feature of quickness is purposely discarded by those describing it, it destroys its value entirely.

I have constructed a modification of this test (Fig. 2) which restores what I think was first designed by its inventor. A double tube box inclosing tubes of ¾″ size, about 18″ long, with proper thickness of division between, to divide the two tubes, through which marbles are run, is placed so that the direction is across the line of vision of the subject, one meter from the patient's eyes, under a good light, without hood or visor "to shut out surrounding objects," which would violate the natural conditions of the gaze. From the point of the division between the tubes, but 8″ or 10″ below, the

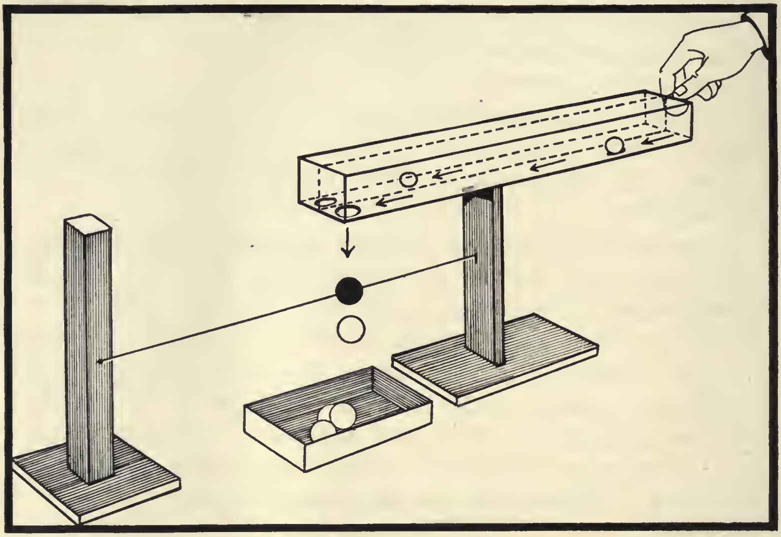

Fig. 2. Hering-Hazen drop-test.

thread with the bead on it is drawn across the line of vision of the subject examined. A marble is placed in one of the tubes by the operator which runs down the slightly inclined plane and strikes a partition at the end which causes it to drop straight down, and the subject designates which side he thinks it dropped by a tap of a small hammer; one tap for near and two for the far side. It is known by the operator on which side it will fall, as he knows in which tube he placed the marble. This test facilitates examination with little labor and gives precision and uniformity. This test seems to fulfill the requirements for measuring distance and speed. Experience will determine many matters of detail not yet made certain.

The four-dot test of Worth (Fig. 3) will serve in detecting

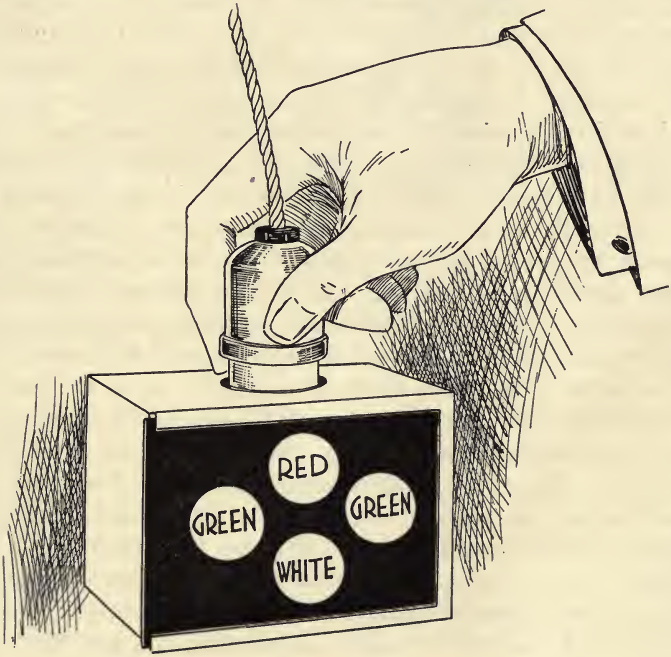

Fig. 3. Worth four-dot test.

unserviceable eyes. I am led to believe that there is much suppression of vision of one eye in short intervals when there is obstruction to fusion. If this test proves to be reliable in this particular, it will add much to our armamentarium.

Nothing so clarifies the understanding on any subject as gathering the experience of rote and theories, in perplexities and failures and adventures to establish principles, generalize ideas, coördinate experiences and allocate sound findings, for presentation to the human mind.

Among the numerous phases of this misunderstood branch of ocular practice are the "imbalances;" these are of that numerous class of affections where there is a want of harmony of action in the muscles of the two eyes. In those cases of turning outward, exophoria, the muscles become enervated and fail to maintain parallelism by the act of fusion; the stronger of the two, or dominating eye (most frequently the right), holds to the line of vision, and the other lags behind. This absence in the act of fusion causes double vision at first, and the strain to resist this tendency heretofore, dating probably months back, has caused much suffering, but now, as the weaker eye takes a departure from equilibrium, and the fusion act is suspended, the annoyance of double vision is soon overcome by an acquired power of suppression of vision of the weak eye, but the patient has only the benefit of a one-eyed person. When this condition comes about, the symptoms of eyestrain subside, and the patient believes that he is better and takes up work that has been tabooed for some time. This manifestation of asthenopia in the muscles is a very common one. With the majority of people this defect or "cast" is not observed until it becomes well marked, but the expert can detect it in its incipiency; the carriage of the head to favor the eye that cannot be controlled, and the sad and anxious countenance, the careful step and avoidance of definite vision when gazing at moving objects are indicative. The deviating eye generally has much less vision than the directing eye, but another phase of this condition, wherein, though the eyes turn from each other, there is an equal amount, or nearly so, of vision, and one eye is brought into line for vision, and sometimes the other (alternating).

A stranger was introduced, lately, as an engineer into one of our shipyards and of course had occasion to consult with the superintendent. This engineer says to one of his fellows: "What eye do you talk to when addressing Smith?" "Well," he answers, "I have known Smith for twenty years and I never know which eye to talk to!"

This deformity of the countenance continually presents a puzzle to most of the people observing them, because it is not understood. It tells of a long siege of asthenopic symptoms, mostly headache for years, that the subject has gone through before the period in which he gave up fusion, and learned suppression of vision. They are now willing to forego the deformity rather than endure the pain if they do not have binocular vision. It is a very significant fact as to causes when we see so many of these, the reflex is upon the mental in many cases, and a large number are in the insane asylums.

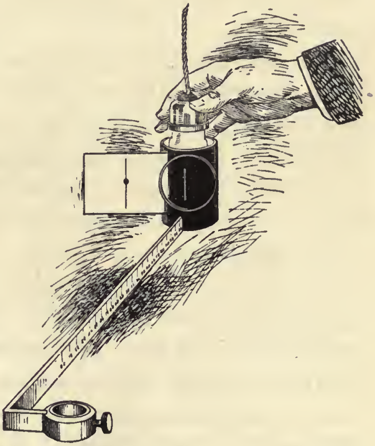

Fig. 4. Convergence rod, with modification of Landolt's ophthalmo-dynamometer.

The photographer knows well how to hide this deformity in his pictures. It is seldom a front view is taken, but a three-quarters turn looking towards the side of the off-eye. Many high officials have one form or another of this deformity. Sometimes there is a deflection upward or downward. The two are often combined.

For these deviations the radical remedy offered is tenotomy. Prisms give temporary relief, but this is but a crutch, and favors the wayward course of things. An operation may correct by putting the balls in proper axes, but this is but a cosmetic effect, for it does not give strength to the muscles to keep the ball in place, and several operations are frequently resorted to.

But the kratometer system of treatment can restore nineteen out of twenty of these cases, providing there is perception of light remaining in the off-eye. Besides the restoration of the position, the retina is cleared up, and good vision is the result in many cases that have had no use of the blind eye for years, and permanency of the repairs made is almost a certainty.

Another division or group of these cases that are differentiated only from the first, is in that there is no or very little imbalance, and that in the progress of the disease there is no escape from the call of fusion, as in the former, in the act of vision, which keeps up the irritation and production of reflex symptoms. To get rid of this discomfort they resort to different expediencies to prevent exciting the fusion act; some school themselves not to respond; they wear dark glasses or tinted and avoid observation; they may sit continually in the dark, especially when the intolerance of light adds another annoyance. These cases dread movement; draw the curtains in the cars or close their eyes. The different circumstances to which they may be subjected, and will avoid as objectionable include: children at play, theaters, movies, car or buggy riding, traveling on shipboard. These may be classed as all of the same nature in asthenopia, but different in degree of severity. As to the reflex symptoms produced, there is no regularity of effect; they depend upon the power of resistance of the nerve irritated. These reflex symptoms, manifested to so great extent in all communities, have been named, but the nomenclature points to no pathology: neurasthenia, migraine, sick headache, car sickness, seasickness, photophobia, nervous prostration.

I do not hesitate to say that the symptoms under these heads can all be removed by the proper treating of this apparatus of the binocular horopterscopic vision. I believe the seat of the disease is here.

Hyperaesthesia of the Retina

There is another group of these cases that is characterized by intolerance of light. Normally the eye is suited to light and the light suited to the eye. In California the sun is as bright as in any part of the United States, and it has become customary, or the fashion with women, to go on the street and in public conveyances without head gear, and boys with delivery wagons go without hats almost the whole of the year.

There having been no adequate cure for this phase of eyestrain has led to the practice of shading; putting on colored glasses or with some tint, and all the theories are rife on shutting out all rays or some parts of the spectrum, so there is a great variety of spectacles worn.

Hyperaesthesia of the retina is a common condition, associated with other symptoms of asthenopia. It has often been noted that cases of eyestrain have hyperemia of the retina, and in advanced cases there is a want of clearness of the vessels, a haziness, which is sometimes diagnosed neuritis. Often, even in severe cases of asthenopia, the outer coats of the eye remain clear and ball white; intolerance of light being the only symptom; there is often emmetropia and orthophoria and duction to half the standard; very frequently there is squeezing of the lids and shedding of tears. I have seen cases of this intolerance, photophobia, who could not bear a ray of daylight, and wore a visor that shut out all light. I have examined these in a dark room with a single candle and found hyperemia, only, confined to the inner coats. These were a great puzzle until I attributed the etiology to muscular asthenopia.

I am reminded that this thesis on this new function in man, so obscure in its nature as to have escaped the recognition of so great a body of scientific men, is in need of minute elucidation. It will not be easy to change to the new view. I am confident of the correctness of my view as to the relation of the muscles to this function and its entity and urge the theory of its diseases. It is founded on the conclusions made after long experience in handling these disordered muscles and studying its subjects both before and after treatment, and I believe the new view will solve many problems in this connection, now hidden in mystery.

At the risk of repetition we will endeavor to further develop the picture of this horopteric vision and materialize what is unseen or unappreciated; its distribution among those with whom we associate every day.

The story of the neurotic, the neurasthenic, the insomnia, the breakdown of the willing and ambitious who start out to make themselves efficient and worthy to attain the higher places of the world, and are blocked in their career at the very threshold of their goal, is a sad one indeed. There are thousands of these who are thus stricken by asthenopia; strong otherwise, and yet this subtile incubus lights upon them, and their expectations are dashed. The general dissemination of this distemper in society is not recognized, because of the difficulty of description and origin. Its effects are attributed to mood, disposition, idiosyncrasy or other fatuous explanations. It obstructs activity, energy, and exertion; it curbs vivacity; it dampens zeal; it bridles the spirit; it eats up ambition; saps aspiration; corrodes vigor; it weaves the insidious ennui and makes in the end, almost sure, a society scrap. The most lively and free disposition it will curb or hamper; it will make peevish and uncompanionable, the heartiest and most lovely. I have seen and treated young children, who had the mannerisms of an old person by this grip of asthenopia. It has turned many a man from a professional career; it has confined subjects of it half of the working hours in bed and a dark room during a whole lifetime. I have reason to believe that moral turpitude has to do with this incubus, and when it is reflected on the mental it unbalances the conscience.

The transition of thought has ever given more satisfaction to him who is engaged in any vocation who can rise from particulars to a general conception of its relation to general principles and feel that his duties are a contribution to a cause that encompasses a lofty purpose. It broadens the mind and inspires the outlook.

This is the psychological change of view in ocular work in this conception of a function that has such a universal application to man's position in general and to his practice of the arts and sciences in particular which has made him ever more in domination of the earth and the conqueror of nature. To have the conception he has in charge the supervision of this wonderful and exceptionally delicate mechanism, meeting the highest skill of the practitioner for its repair, gives him higher conceptions of his calling, and dignity to his position.

To say that the human race is more dependent upon the healthfulness and perfection of this function than upon any other faculty of the body is no exaggeration. It gives the health officer and the employer a clue for judgment in selection of persons for duties to perform and for protracted study to prepare, for it is with this faculty in perfection that works out to practical use the ideas of inventors. The safety of the public conveyances depends largely upon this faculty being perfect in the motorist or engineer who guides them, yet not now tested by those who are supervising these public interests.

Here is the field where visual optics, psychology and sociology can meet in organization and in specialization to bring to the front the highest of human skill to its own.

The doctrine that the diseases of this function are in the motor apparatus is a pathological one instead of a dynamic or mechanical fault is satisfactory in, that under it, the eyes have been restored to their function with surprising rapidity.

The road is a safe one for experiment, and although everything connected with unserviceable eyes may not be found in the working, it will remove many difficulties by exclusion and furnish a clear path to further discoveries. It relegates the dangers of knife and scissors to the exceptionals.

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The Power of a Spectacle Lens

A. Estelle Glancy, Ph.D.

THE power of a lens and the focal length of a lens convey the same information; one is the reciprocal of the other. Either one of these terms describes how much the lens converges or diverges a parallel beam of light which enters the lens along its axis. Either one fixes the point on the axis where the rays of light come to a focus, real or virtual, as the case may be. Now to define this point we must have some fixed point of reference from which to measure and it is evidently some point common to the lens and the optic axis.

It is commonly understood, when we say that the power of a lens is +1 D, that the light from a distant source comes to a focus at a point one meter from the lens. This is often a sufficiently accurate statement, for we may not care to know the power within close limits of error or may be discussing a theoretical lens of ideal thinness. But suppose we have a lens of commercial thickness and wish to know the power accurately. From what point of the lens shall we measure, from a surface or from some point inside the lens? For some purposes we use the rear surface as the point of reference. The distance to the focus is called the "back focus." In some cases we use a point inside the lens which is one of the two "principal points" of the lens, points whose positions depend upon the shape of the lens. The distance from the second principal point to the secondary focus is called the equivalent focal length of the lens or the E. F. L. And we shall find later that the distance from the front surface to the primary focus, or "front focal length," as it is called, is the reciprocal of the neutralizing power.

Power of a Spectacle Lens

There are four current expressions for power which should be clearly understood.

Approximate Power (D_1+D_2). Let D_1 be the power of the front surface and D_2 be power of rear surface. Then D_1+D_2 is a good approximation to the power of a thin lens. It is found in all elementary text books and therefore is in current use among students. For accurate work and for thick lenses this approximation is not good enough.

Equivalent Power. In more advanced optical work power is commonly expressed as the reciprocal of the equivalent focal length. The term "equivalent power" distinguishes this definition from the others by a properly qualifying adjective[1]. Equivalent focal length is a very useful conception and has an important application to a compound lens system, for it tells us where a single thin lens could be placed to give the same magnification. We shall endeavor to show that "equivalent power" which has been employed extensively in spectacle work is a less useful quantity than "effective power" as defined below.

Effective Power. The development and improvement in the design of spectacle lenses and trial sets has led to the introduction of the "back focus" and its reciprocal, "effective power." This is sometimes called "vertex refraction," which is a translation of the German "scheitel refraction," introduced by von Rohr. While the term "vertex refraction" is due to von Rohr (1912), the significance of the back focus was recognized much earlier. As early as 1908 the Optical Society (London) adopted the report of its Optical Standards Committee on the Standardization of Trial Cases in which Table III gives not only the power of the trial lenses, but also the back focal length. We shall use the expression "effective power" and in the course of this paper we hope to justify the preference.

Neutralizing Power. We are all familiar with the practice of neutralization upon which the optician relies so much.

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[1] Used by Laurance, *General and Practical Optics, page* 222.

The basic idea of neutralization is very simple. For example, the optician makes a −2D lens. He holds it against a +2D lens from the trial set. If the combination shows *no* power he is satisfied that the −2D lens is ground correctly. For weak powers this practice is without question; for higher powers it is readily proved that neutralization is not, in general, justified. In the report of the Standardization Committee referred to above, the use of trial lenses for neutralization purposes is carefully discussed. At that time the demand from manufacturers and others to maintain a neutralization basis for trial sets was so insistent that the following recommendation was offered and accepted. The negative lenses (biconcave) were marked with their real "equivalent powers" and the positive lenses (bi-convex) were marked with corresponding "nominal" powers but were ground so as to neutralize the negatives. For example: a −20 D lens was neutralized by a +20 D lens (nominal power), of which the true equivalent power was +18.83 D. A statement giving the true powers of the standard positives was required to be pasted in each trial case.

Numerical Comparisons

There are some simple formulæ for the calculation of equivalent power, effective power and neutralizing power. They are so simple in form that it is easy to make instructive comparisons showing upon what the numerical differences depend.

(1) Equivalent Power $= D_1+D_2-sD_1D_2$

(2) Effective Power $= D_1+D_2+sD_1^2+\dots$

(3) Neutralizing Power $= D_1+D_2+sD_2^2+\dots$

$D_1 =$ power of front surface

$D_2 =$ power of rear surface

$$s = \frac{\text{center thickness}}{\text{index of refraction}}$$

The first formula is rigid; the other two are not. Each succeeding term of (2) and (3) beyond the third is smaller than the one preceding. In all but the higher powers the first three terms are sufficient. Effective power and neutralizing power can each be expressed by rigid formulæ, but the forms given here serve better for the comparisons which we wish to make. In the numerical tables following the next term was included.

All three formulæ contain D_1+D_2, *i. e.*, the sum of the powers of the front and rear surfaces, and the remaining term shows how much the power differs from this approximate expression which is so often used. Let us then consider the third term in each.

It is evident from the term $-sD_1D_2$ in equation (1) that equivalent power depends upon the thickness and the powers of the two surfaces, but parallel light can enter from either side and the equivalent power remains the same. This may, at first sight, seem to be an advantage, but it will be shown later, from figures, that the power is the same because in one case it is measured from the second principal point and in the other from the first principal point.

We see from equation (2) that the third term is independent of the rear surface. Evidently then, effective power varies with the shape of the lens. If we reverse the direction from which parallel light enters, we change the effective power.

Similarly, the third term in (3) is independent of the front surface and varies with the shape of the lens. In fact there is a relation between (2) and (3). If we write D_1 for D_2 and D_2 for D_1 throughout in (3) we have (2). In other words, the neutralizing power of a lens is equal to its effective power when the lens is reversed. Suppose we have three positive lenses, the sum of the powers of the two surfaces being +16, one a bi-convex, another convexo-plane, and the third a meniscus with −6 on the rear surface. The following short table shows what must be added to +16 to give

	Bi-Convex	*Convexo-Plane*	*Meniscus −6*
Equivalent power	−0.28	0.00	+0.57
Effective "	+0.28	+1.18	+2.30
Neutralizing "	+0.28	0.00	+0.16

equivalent power, effective power, and neutralizing power, respectively.

On pages 76-77 is a large table showing these quantities, from which it can be seen how they vary with the power of the lens and with the shape of the lens. Using the same example, a meniscus with rear surface −6 and front surface +22, $D_1+D_2=+16$. The effective power is different from +16 by +2.30 D, its equivalent power is 0.57 greater and its neutralizaing power is 0.16 greater. Evidently the effective power is 2.14 D greater than its neutralizing power; *i. e.*, a meniscus −6, whose effective power is +18.30 would neutralize a lens whose effective power is −16.16 when the convex side of the meniscus is one of the contact surfaces.

Accompanying this article are given six figures corresponding to cases $D_1+D_2=+16$ and $D_1+D_2=-16$ in the tabulation given in Table I. In each case parallel light enters from the left; F′ is the secondary focus and H′ the secondary principal plane. Similarly F and H are the primary focus and first principal plane respectively. Let us come back to the fundamental distinctions between the definitions for equivalent power, effective power, and neutralizing power.

TABLE I

$$\text{Difference between}\left\{\begin{array}{l}\text{Equivalent power}\\ \text{Effective}\quad\text{"}\\ \text{Neutralizing}\quad\text{"}\end{array}\right\}\text{and }(D_1+D_2)$$

NOTE.—To get power add quantities in table to (D_1+D_2)

Positives

D_1+D_2	Equivalent				Effective				Neutralizing				Thickness
	Bi-Convex	Convexo Plane	Meniscus $D_2=-3$	Meniscus $D_2=-6$	Bi-Convex	Convexo Plane	Meniscus $D_2=-3$	Meniscus $D_2=-6$	Bi-Convex	Convexo Plane	Meniscus $D_2=-3$	Meniscus $D_2=-6$	
0	0.00	0.00	+0.01	+0.03	0.00	0.00	+0.01	+0.03	0.00	0.00	+0.01	+0.03	1.2 mm
+2	0.00	0.00	+0.02	+0.06	0.00	+0.01	+0.03	+0.08	0.00	0.00	+0.01	+0.05	1.9
+4	−0.01	0.00	+0.04	+0.10	+0.01	+0.03	+0.08	+0.17	+0.01	0.00	+0.01	+0.06	2.6
+6	−0.02	0.00	+0.06	+0.15	+0.02	+0.08	+0.17	+0.32	+0.02	0.00	+0.02	+0.08	3.1
+8	−0.04	0.00	+0.09	+0.22	+0.04	+0.17	+0.32	+0.53	+0.04	0.00	+0.02	+0.09	3.8
+10	−0.08	0.00	+0.12	+0.30	+0.08	+0.32	+0.55	+0.84	+0.08	0.00	+0.03	+0.11	4.6
+12	−0.12	0.00	+0.15	+0.37	+0.12	+0.52	+0.80	+1.16	+0.12	0.00	+0.03	+0.12	5.1
+14	−0.19	0.00	+0.19	+0.46	+0.19	+0.79	+1.18	+1.65	+0.19	0.00	+0.03	+0.13	5.7
+16	−0.28	0.00	+0.25	+0.57	+0.28	+1.18	+1.70	+2.30	+0.28	0.00	+0.03	+0.15	6.4
+18	−0.39	0.00	+0.30		+0.41	+1.68	+2.36	+3.12	+0.41	0.00	+0.03	+0.17	7.2
+20	−0.49	0.00			+0.51	+2.17	+2.91		+0.51	0.00	+0.03		7.3

Negatives

D_1+D_2	Equivalent				Effective				Neutralizing				Thickness
	Bi-Concave	Plano-Concave	Meniscus $D_2=+3$	Meniscus $D_2=+6$	Bi-Concave	Plano-Concave	Meniscus $D_2=+3$	Meniscus $D_2=+6$	Bi-Concave	Plano-Concave	Meniscus $D_2=+3$	Meniscus $D_2=+6$	
0	0.00	0.00	+0.01	+0.03	0.00	0.00	+0.01	+0.03	0.00	0.00	+0.01	+0.03	1.2 mm
−2	0.00	0.00	+0.01	+0.04	0.00	0.00	+0.01	+0.03	0.00	0.00	+0.02	+0.05	1.2
−4	0.00	0.00	+0.01	+0.04	0.00	0.00	+0.01	+0.02	0.00	+0.01	+0.04	+0.07	1.0
−6	−0.01	0.00	+0.01	+0.04	0.00	0.00	0.00	+0.02	+0.02	+0.02	+0.05	+0.08	0.7
−8	−0.01	0.00	+0.01	+0.04	+0.01	0.00	0.00	+0.02	+0.01	+0.03	+0.06	+0.09	0.7
−10	−0.01	0.00	+0.01	+0.05	+0.01	0.00	0.00	+0.02	+0.01	+0.05	+0.08	+0.13	0.7
−12	−0.01	0.00	+0.01	+0.05	+0.02	0.00	0.00	+0.02	+0.02	+0.07	+0.12	+0.17	0.7
−14	−0.02	0.00	+0.02	+0.06	+0.02	0.00	0.00	+0.02	+0.02	+0.09	+0.14	+0.20	0.7
−16	−0.03	0.00	+0.02	+0.07	+0.03	0.00	0.00	+0.02	+0.03	+0.13	+0.17	+0.24	0.7
−18	−0.04	0.00	+0.02	+0.07	+0.04	0.00	0.00	+0.02	+0.04	+0.17	+0.21	+0.29	0.7
−20	−0.05	0.00			+0.05	0.00	0.00	+0.02	+0.05	+0.20	+0.27		

Positive Lenses
$D_1 + D_2 = 16$

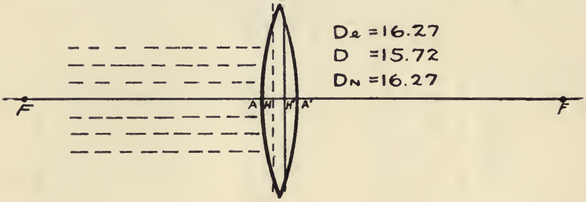

Fig. I

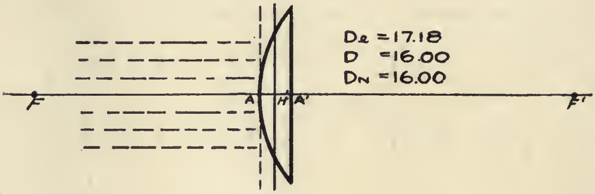

Fig. II

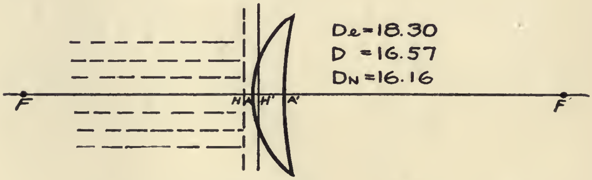

Fig. III

Figs. 1, 2 and 3. Positive lenses, showing principal planes.

In any elementary text-book figures similar to figure 1 are given, showing the lens, the two foci, and the two principal planes. The primary focus F is the point from which the light of a point source diverging and entering the lens is rendered parallel upon emergence. The point F′, the secondary focus, is the point to which entering parallel rays

Negative Lenses

$D_1 + D_2 = -16$

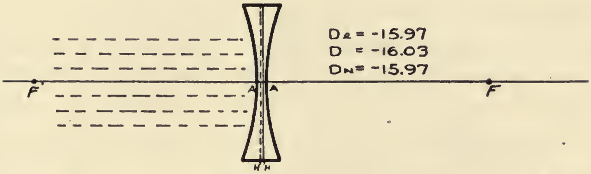

Fig. IV

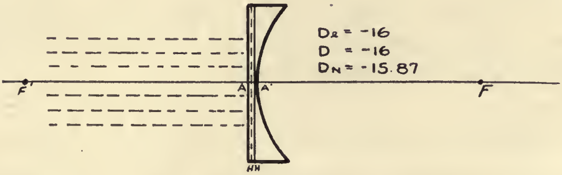

Fig. V

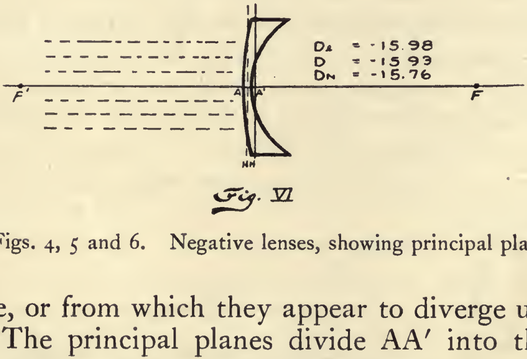

Fig. VI

Figs. 4, 5 and 6. Negative lenses, showing principal planes.

converge, or from which they appear to diverge upon emergence. The principal planes divide AA′ into three equal parts and HF = H′F′. Note from figures 1, 2, 3, that the principal planes move to the left as the shape of the lens changes. Similarly for the concave lenses, figures 4, 5, 6. It is true, in each case, as was said above, that the equivalent power is independent of the direction of the light, *i. e.*, HF = H′F′ but the planes H and H′ are not fixed in relation to the lens, and it is clear that if a spectacle lens is measured in terms of equivalent power, the position of F′ with respect to the lens depends upon the shape of the lens and is measured, in general, from some point within the lens.

It is for this reason that the back focal length and effective power have grown in favor until the best trial sets and lenses are designed and manufactured and marked so. Effective power is the reciprocal of A′ F′ so we always know, whatever the shape of the lens, how far back of the rear surface the focal point is situated. Its use implies, of course, that the spectacles shall be worn at some pre-determined distance in front of the cornea: (this is true in any case). The distance 14mm. has been universally adopted because at this distance the magnification of objects is unity.

Effect Upon the Eye of Position of the Lens

There is a curious custom which has a bearing on the question of the proper position of spectacles. It is sometimes observed that a person who should wear bi-focal glasses lowers his spectacles for distant vision far down on the bridge of his nose and reads. This habit has a simple scientific explanation; the spectacles so worn are stronger in effect, as the following figure (figure 7) will show. Suppose a lens in position L (figure 7) brings light to a focus at F′ which is distant the length AF′ from the point A. If we move

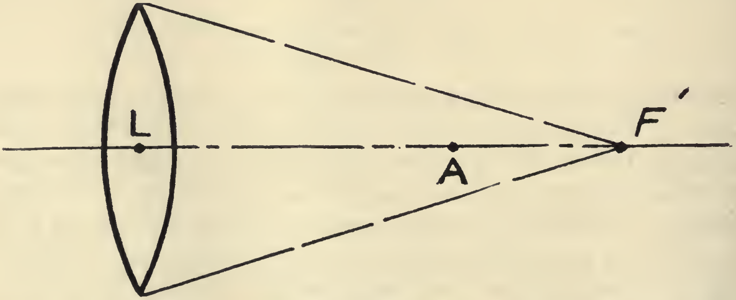

Fig. 7. Illustrative of the effectivity of a lens with reference to a given point.

the lens away from A the focal point moves nearer A; *i. e.*, with respect to A the lens is stronger in the second position. Or, in other words, a weaker lens in the second position would bring the light to a focus at F′. A lens is more or less effective in bringing light to a focus at a definite distance from a fixed point according to its position with respect to that point.

A formula to express this idea of change in power with respect to a point A as the lens is moved is found in Laurance, *General and Practical Optics*, page 192. It will be found upon reading that Laurance uses the term "effective power" also, and in a larger sense than is used here, but there is no conflict of definition. He makes the statement: "If any lens is in contact with a given plane, then the effectivity at that plane is represented by the power of the lens itself." This is equally valid whether we think in terms of EFL or back focus.[1] Now in the design of spectacles the point A may be at the cornea or at any fixed known distance from it. Since the point 14mm in front of the cornea has the distinction of giving unit magnification, and spectacles are worn at this position, this should be the fixed point of reference with respect to which power is measured. Regardless of the shape of the lens, the position of the focal point in relation to the eye is known. In other words, effective power, as we have defined it, gives the true corrective effect of the lens upon the eye. The lens should be designed for this corneal distance, the trial set should be marked with effective powers, the trial frame should have adjustment for corneal distance and the spectacles should be worn at the same distance. It is just as important to wear a carefully designed lens at 14mm as it is to make the lens calculations for this distance. Suppose a +10D lens (effective power) is designed to be worn at 14mm and is worn at

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[1] In another reference Laurance uses the term "effective power" to mean specifically the power of an ophthalmic lens with relation to the principal planes of the eye. See *Visual Optics and Sight Testing*, page 274.

16mm. The back focus is 100mm and an increase of 2mm gives an effect upon the eye of

$$\frac{1}{0.098} = 10.2\text{D}$$

Marginal Power

Lens design has now reached the point where the lens errors near the margin are reduced. Suppose we are concerned with such a design. How is "effective power" measured near the margin? In correcting marginal error we are concerned with oblique vision or the motion of the eye about its center of rotation. Evidently then we should measure back focal length always from a distance 14mm from the cornea (27mm from the center of rotation), and the effective power is then referred, not to a plane, but to a circle of 27mm radius.

Effective Power vs. Vertex Refraction

The expressions "vertex refraction" and "effective power" mean the same thing at the center of the lens, but *vertex* refraction can have no meaning, except at the center, for the *vertex* is the intersection of the optic axis and the center of the rear surface. Neither does it have as direct a suggestion of meaning. By effective power we mean power so measured that it gives directly the corrective effect of the lens upon the eye when it is worn at the universally adopted distance of 14mm.

Relation Between Effective Power and Neutralizing Power

Effective and neutralizing powers bear a simple relation to each other. That two lenses having a common axis shall neutralize, only one condition needs to be fulfilled; namely, that the secondary focus of the first shall coincide with the primary focus of the second. The lenses may or may not be in contact. (Two negatives cannot be made to neutralize because both foci are virtual, but two positives on opposite sides of the common focal point will neutralize.) Suppose parallel light enters a positive lens and is converging toward F′. Then if a negative lens is placed in the converging beam so that its primary focus F coincides with F′ it will render the beam parallel upon emergence by definition of primary focus.

Now neutralization of ophthalmic lenses is always accomplished by holding the lenses in contact, hence the second lens must have a front focal distance equal to the back focal distance of the first lens. Neutralizing power is defined to be the reciprocal of the front focal distance. Now front focal length becomes back focal length when the lens is reversed, hence neutralizing power is equal to the effective power of the lens reversed and a single formula serves for both as mentioned above, provided due regard is shown for the interchange of D_1 and D_2.

Neutralization

In making neutralization tests we have to remember that effective power and neutralizing power are numerically interchangeable with reversal of the lens and that the front surface of the known lens must be one of the surfaces of contact. The other surface of contact will be the rear surface of the unknown lens.

To bring out the same idea in a somewhat different way: Suppose a bi-concave trial lens is used to neutralize a strong positive meniscus. If the course of entering parallel light is followed through the combination with convex surface against concave (light may enter from either side) it will be seen that the power of the meniscus given by neutralization is measured from the convex surface; *i. e.*, the lens should be worn with convex surface toward the eye.

It might seem at first sight that a bi-convex lens would neutralize a bi-concave lens of the same curvature. This is

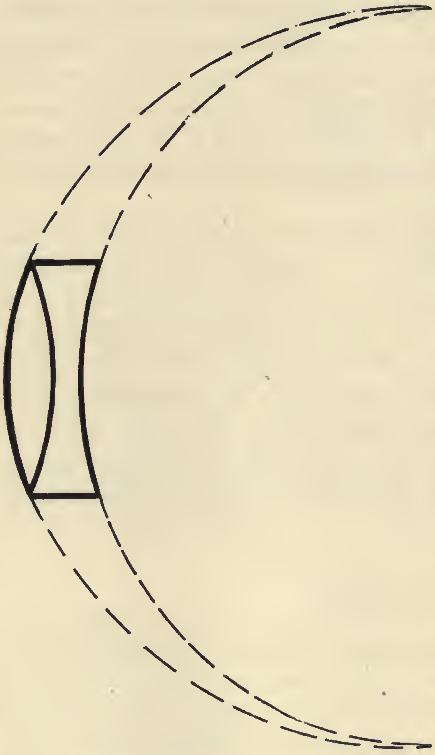

Fig. 8. Illustrative of why lenses of equal power fail to neutralize.

true for weak powers only. If we draw a cross section of the lenses and extend the outside curves it is at once evident that the combination is a section of a larger lens of meniscus shape which is essentially positive (figure 8). This was clearly brought out in a pamphlet entitled *Why Strong Contra-Generic Lenses of Equal Power Fail to Neutralize Each Other*, by Charles F. Prentice, 1899.

For perfect neutralization of a strong bi-convex and bi-concave it is necessary that the curvature of the concave lens shall be a little steeper. This means a very thin air space at the center. In practice, however, neutralizing sets are manufactured including 20 D. This is accomplished by reducing the diameters. The lenses are designed to have equal effective powers and although they cannot be made to neutralize, theroretically speaking, they do so in practice, for the very small difference from complete neutralization is less than the eye can readily observe, amounting to a maximum of 0.04 D. for a full size lens (40mm).

Summary and Conclusions

(1) From the above considerations of theory and practice

and development of the spectacle industry, whether from the standpoint of the designer and manufacturer or the refractionist or the wearer, it is of importance to recognize the physical significance of the power of a lens and to know its several meanings and uses.

(2) We have seen that the important characteristic of a lens is its effect upon the eye and that this depends not only upon the curves of the two surfaces, but also upon the thickness, the shape and the position before the eye.

(3) Neutralization must be practised with discrimination if used at all.

(4) Trial sets and newly designed spectacles are calculated for and marked with effective power. The meniscus lens is very largely used and will continue to be used, for it gives a wider field of vision and is capable of better marginal correction. With these developments we must have a clearer understanding of power and neutralization and of the relation between them.

Recognition is due Mr. E. D. Tillyer of the Research Department of the American Optical Company for many suggestions in connection with the above presentation.

Research Laboratory,
American Optical Company.

Abstracts and Reviews

Twenty-three Types of Optical Glass

Robert J. Montgomery

TO THE average mind the distinction between optical glass and other types of glass is not clear, and the divisions of the field with the limits of optical properties which may be obtained are not fully catalogued. In this paper an effort is made to classify the ordinary types of optical glass and to discuss their composition in general terms.

The word *optical* with reference to glasses refers to their behavior toward transmitted light. This behavior is due to the composition of the glass. Each constituent has an effect on the index of refraction and the dispersion of the glass and those two properties identify the glass as being of a certain type. The main difficulty in making optical glass is in obtaining the required optical properties and at the same time so combining the constituents and handling the material that a good quality of glass will result.

A study of the composition and optical properties of nearly ninety glasses, combined with the author's practical experience in the manufacture of optical glass, brings out the following points: (1) All the glasses may be plotted on coördinate paper allowing the dispersion to be represented by the horizontal distance and the index by the vertical distance. (2) That the glasses fall into natural groups in the field plotted and may be divided into types according to composition. (3) That there are 23 ordinary types of optical glass, each type embracing a number of glasses quite similar in optical properties, composition, and method of manufacture. (4) That the composition of the glasses may be

PLATE I

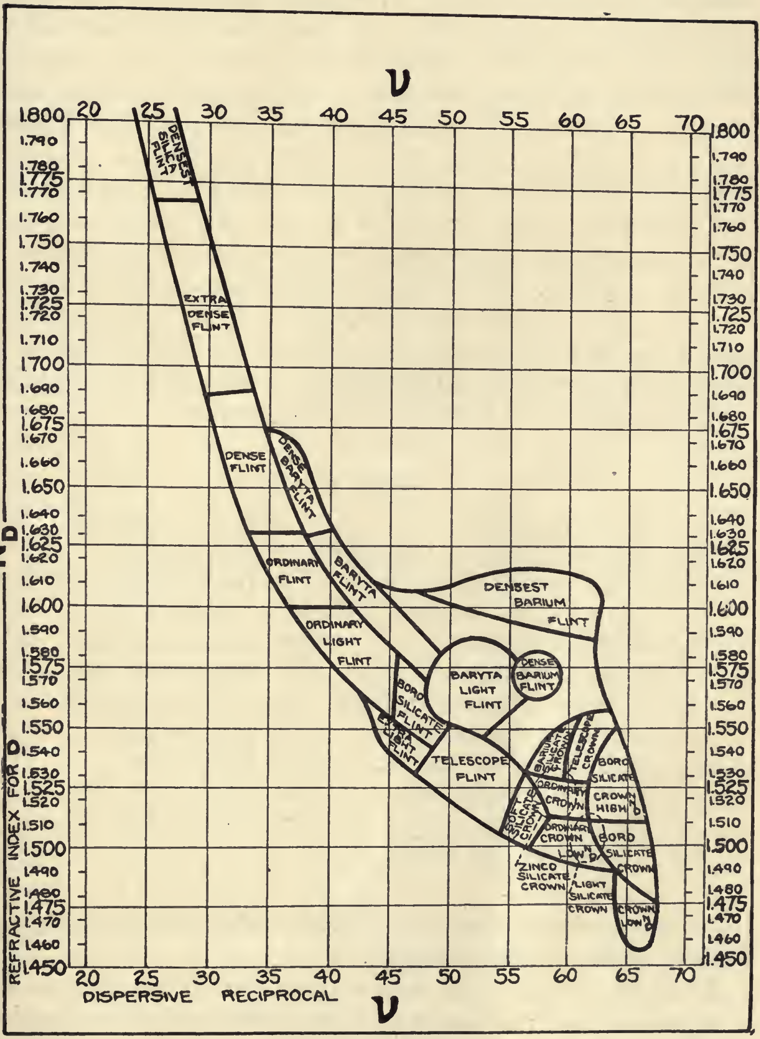

Plate I. Relations between refractive index and dispersive reciprocal.

divided into two divisions, (a) fundamental oxides affecting the optical properties, and (b) control chemicals which affect the melting behavior. The fundamental oxides are SiO_2, K_2O, Na_2O, CaO, PbO, ZnO, B_2O_3, and so forth, while by the control chemicals are meant the proportioning of carbonates, nitrates, chlorides, and sulphates or the use of As_2O_3 and Sb_2O_5 to obtain good melting conditions. In some cases the fundamental oxide may be used as a control chemical when the optical properties are not affected by so doing or when the composition may be corrected for the addition of such chemical. Plate 1 shows the fields occupied by the various types of glass with an index 1.45 to 1.800 and dispersion value from 20.0 to 70.0. These are listed in table 1. The ones marked with an asterisk are now being successfully made in commercial quantity in this country.

TABLE I

1. Borosilicate crown
*2. Borosilicate crown high N_D
3. Crown of low N_D
4. Light silicate crown
*5. Ordinary crown
6. Telescope crown
*7. Ordinary crown of low N_D
8. Soft silicate crown
9. Zinc silicate crown
10. Barium silicate crown
*11. Dense barium crown
*12. Densest barium crown
*13. Baryta light flint
14. Baryta flint
15. Dense baryta flint
*16. Telescope flint
17. Extra light flint
18. Borosilicate flint
*19. Ordinary light flint
*20. Ordinary flint
*21. Dense flint
*22. Extra dense flint
23. Densest silica flint

As will be noted, there are 12 out of the 23 ordinary types of glass made in this country.

A study of the plate shows that very large changes in composition are necessary to change the optical properties to any extent; that is, the index in the first decimal place and the dispersion in the tens place. At the same time it is evident that if the index of refraction and dispersion are to be kept constant for any one glass any small variation in composition will be disastrous. A variation of 0.1 per cent. in the amount of the important oxides will affect the index from 0.5 to 1.0 in the third decimal place and the dispersion from 1 to 5 in the first decimal place.

(Abstracted from *Journal of the American Ceramic Society*, Vol. 3, page 404, 1920.)

Routine Office Measurement of Stereopsis

David W. Wells, M.D., F.A.C.S.

VISIBILITY and monocular parallax are the most important factors in an ocular estimation of the relative distance of two objects. Eaton (*British Journal of Ophthalmology*, Vol. III, 1919) has stated the relative values of these different factors. Howard (*Transactions American Ophthalmological Society*, 1919) has shown that while monocular judgments are valuable, the binocular parallactic angle is absolutely essential to any refinement of the faculty. This test has been applied to aviators, but it is likely that when all the facts are known, visual tests will not stop with measuring the acuity of each eye and other simple tests but that a certain standard of stereopsis will be required of engineers, chauffeurs, street-car motormen, and the like.

In 1899, Pulfrich announced that persons with normal eyes have a power of perception of depth of 10 seconds. In 1908, James stated that he found that the angle of binocular parallax corresponded to the angle of visual acuity; that is, if each eye possessed an acuity of 1 minute, the angle of binocular parallax was 1 minute. In 1919, Howard, dealing with picked men, showed that an individual with normal eyes of equal acuity and orthophoria should be able to distinguish a depth difference of 1.5 cm. at 6 meters, which corresponds to a parallactic angle of 10.2 seconds for a pupillary distance of 60 mm.

Both James and Howard speak of the importance of securing equal and uniform illumination. The apparatus of Cohen (*Archives of Ophthalmology*, March, 1919) overcomes this objection, and would be quite inexpensive if there were sufficient demand to make them in quantity. Dr. Cohen very kindly loaned his apparatus to the writer, giving per-

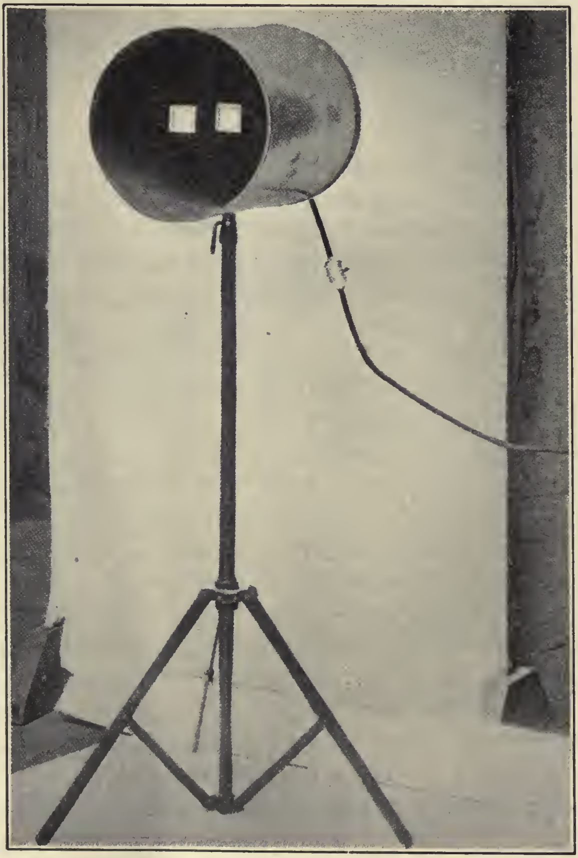

Fig. 1. An instrument for the measurement of stereopsis.

mission to make such changes as were found desirable. Figure 1 shows it so modified.

It consists of a sheet iron cylinder 30 cm. diameter and 40 cm. long, open at one end, mounted on a tripod. Originally it had four lights arranged quadrilaterally, but this has been simplified by reducing the number to two, in a horizontal plane. The miniature lamps are on the ends of tubes which pierce the back of the cylinder and have an antero-posterior adjustment of about 20 cm. The lights are covered with a white translucent glass and show evenly luminous circles of 28 mm. diameter. These were so arranged that block letters or colored glass might be used in front of them. As now used, they are covered with black plates having openings of 1 cm. One is fixed and the other plate is adjustable horizontally so as to make the separation equal to the subject's P. D. The whole affair is dead black, so that the observer sees only the two luminous disks. There is thus no possibility of utilizing any monocular parallax.

James says that the posterior stick should be .5 mm. larger than the anterior, so that both would subtend the same visual angle, as otherwise the size of the retinal image might influence the judgment of the distance.

In order to make this difference exactly correct for varying distances, one of the lights was covered with an iris diaphragm, but in figuring out what this allowance should be, it was found that for a depth difference of 20 mm. the tangents of the visual angle vary only .03 mm.; for 200 mm., .3 mm. As the normal depth difference is 15 to 20 mm., it was evident that the size of the retinal image would not be appreciably influenced. The iris diaphragm was therefore discarded and two lights are of same diameter, 1 cm. The ends of the tubes which project behind the cylinder are marked off in 5 mm. divisions.

The standard conditions suggested are as follows:

1 The apparatus shall be placed at 6 m. from observer.

2 The luminous disks shall be 1 cm. diameter.

3 Separation of disks equal to subject's P. D.

If these conditions are followed, the results will be comparable with the experiments of James and Howard.

In using the instrument, the subject is asked to close his eyes and the depth difference arranged at 40 or 50 mm. If, on opening the eyes, this difference is quickly recognized, the process is repeated with a smaller difference until the subject makes a mistake or is unable to see any difference. A few trials will suffice to determine a difference which is correctly stated. Howard made twenty trials and considered that when answers were 75 per cent. correct the subject's threshold had been determined. This seems to the writer a very unnecessary refinement, as a few trials suffice.

This subject is one of importance and it is to be hoped that further data will be forthcoming on this matter.

(Abstracted from *Archives of Ophthalmology*, Vol. XLIX, pages 64-69; 1920.)

Lantern and Apparatus for Testing the Light Sense and for Determining Acuity at Low Illuminations

Prof. C. E. Ferree and G. Rand, Ph.D.

AN APPARATUS for determining the acuity at low illuminations or the effect of change of illumination must possess the following: (1) A means of changing the illumination by small amounts over a wide range, beginning at or below the threshold for the test object employed without changing the color value of the light. If in making this change the color value of the light is altered, it is obvious that another factor affecting the results is introduced. (2) A means of keeping constant for an indefinite length of time any desired intensity of illumination and of reproducing this intensity at will; also the test object must be uniformly illuminated. (3) A means of specifying accurately, at any point in the scale, the intensity of light falling on the test object. (4) It is desirable that the apparatus employed for controlling the illumination shall be usable with the test objects already accepted in clinic practice.

In order to insure uniformity of illumination at or near the threshold, it was deemed necessary to select an aperture sufficiently small to permit of its uniform illumination and of projecting the magnified image of this aperture on a test card. That is, an aperture was selected of such a size and shape that when magnified five-fold it gave a band of light which just blocked off one line of the test letters. It is obvious that this aperture could be made of different sizes and shapes depending upon what is wanted in the projected image.

The changes in intensity of light were produced by means of an iris diaphragm. When such a diaphragm is placed at the front or back surface of the focussing lens, changes in the flux of light can be produced without any alteration in the size or shape of the image produced by the lens, just as happens, for example, in the action of the iris of the eye.

Figure 1 is reproduced from a photograph of the apparatus. At A is represented the body of the lantern. This contains the source of light, a well seasoned type C Mazda lamp of a wattage depending on the range of illumination desired; an aperture; diffusing surfaces; focussing lenses and the iris diaphragm.

An aperture is cut in the center of the cap covering the inner end of the projection tube B. This aperture is covered with diffusing screens of ground glass in order to aid in an even illumination. At the further end of the projection tube is a brass ring and collar carrying the focussing lens. Just back of the lens and mounted in the same ring is the iris diaphragm. On the circumference of the diaphragm is mounted a pointer which, as the diaphragm opens and closes, moves over a translucent millimeter scale. On the platform supporting the lamp box are mounted a small

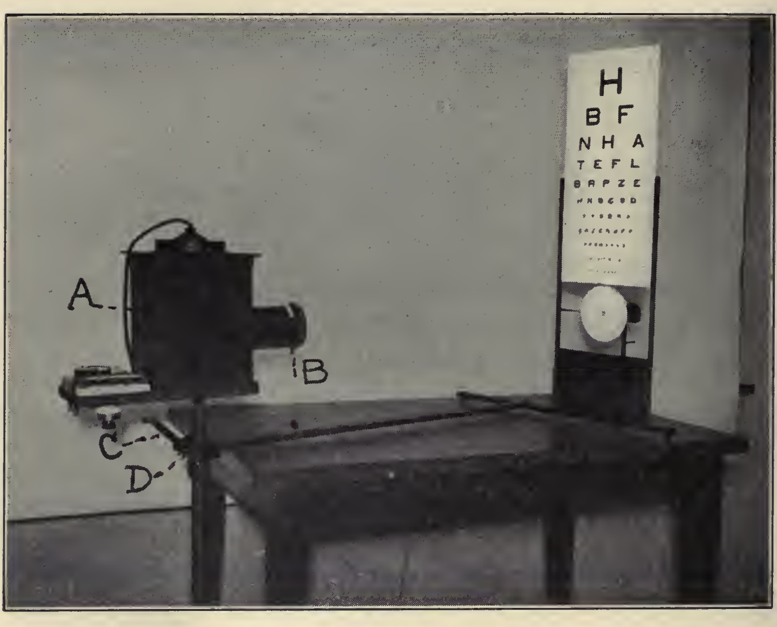

Fig. 1. A lantern for testing the light sense and visual acuity.

ammeter and a control rheostat to guard against fluctuations in the current. The box can be raised by means of a rack and pinion device so that any portion of the test card can be illuminated. The equivalents of the illumination given by any setting of the iris diaphragm were determined in meter-candles at the test-card by removing the lamp box and mounting it on a photometer bar at a distance from the photometer head equal to its original distance from the test-card. The scale was then gone over point by point.

In their experimental work the authors preferred to use a single test-character instead of the letters on the Snellen chart. The reasons for the preference are: (1) A test-letter may be recognized when it is not seen at all clearly. Recognition is too dependent on extraocular functions to be used with precision as a measure of ocular capacity. (2)

The different letters of the Snellen chart set an unequal task for the resolving power of the eye. (3) An objective check is had on the correctness of the judgment. This is especially helpful in case of children and the unintelligent, untrained and subjective type of adult. (4) By the use of the same test character, turned in different directions at will, all possibility of learning the test series is eliminated. Also the test object becomes much more valuable for the detection of astigmatism. (5) At low illumination the eye fatigues very rapidly. Thus if the task is the reading of the whole line of letters, the results obtained measure not only acuity but the power to sustain acuity which may or may not be compatible with the purpose of the test.

The apparatus has the following clinical uses: (1) When used with a higher watt lamp it provides an acuity test apparatus or lantern with which the test card can be illuminated by a constant and known intensity of light, abundantly high in the scale to meet the Snellen standard of acuity. (2) When used with the 100-watt lamp it serves for those cases in which there is need for testing scotopic or twilight vision, and the amount and rate of scotopic adaptation. It thus affords a very feasible and precise means of testing the light sense in so far as it affects the power to see clearly, the effect with which we are the most concerned for the greater part of our working lives. Also the 100-watt lamp is sufficient for the testing of photoptic acuity in the case of the greater number of eyes which would ordinarily be graded as normal. (3) If the image of the aperture is projected on a blank white surface of good reflecting power, more particularly if its size and shape are changed to that of square or circle, of dimensions favorable for making a sensitive judgment, the apparatus can be used with an equal degree of precision and convenience for testing the light sense directly, in terms of the amount of light required to arouse just noticeable sensation. That is, the threshold of sensation can be determined in terms of meter-candles of light falling on the test surface. (4) By making it possible to determine with great exactness the minimum of illumination at which the test object can just be discriminated, the apparatus provides a very sensitive means for detecting small errors in refraction and in their correction, as will be demonstrated in another paper. (5) Sensitivity for detecting small errors in refraction and their correction could also be added to the acuity test, by using test objects of slightly variable size. However, no means has as yet been provided for making small changes in the size of any acuity object, sufficiently complicated in form to test simultaneously the resolving power of the eye in any great number of meridians which is, we believe, a very important feature in determining the exact location of an astigmatism, or the exact amount and placement of its correction.

(Abstracted from the *American Journal of Ophthalmology*, Vol. 3, pages 335-340, 1920.)

Visual Acuity at Low Illumination and the Use of the Illumination Scale for the Detection of Small Errors in Refraction

Prof. C. E. Ferree and G. Rand, Ph.D.

IN A thorough test of vision in persons following vocations requiring keenness of discrimination at low illuminations, the following must be considered: (1) The minimum amount of light required to discriminate the test-object before dark adaptation, (2) the same, following a selected period of dark adaptation and (3) the rapidity as well as the amount of gain in acuity during the process of adapting.

Tests have shown that a sensitive light control can be used with great precision in detecting small errors in refraction and their correction. This is true because of the fact that acuity changes slowly with change of illumination, small differences in acuity corresponding relatively to large differences in illumination for all but very low illumination. The minimum illumination at which a test-object subtending the standard visual angle becomes discernible affords a very sensitive test upon relatively slight differences in acuity.

In making tests with both dark and light adapted eyes as to the minimum illumination necessary for discrimination, a Snellen letter E and the broken circle, each subtending a 5 minute angle, were employed. The broken ring was found superior in showing a greater range of individual difference. Also, a greater range of individual dfference was found for the tests taken before the period of dark adaptation than for those taken after the 45 minute adaptation period. Another extremely interesting result is that, without exception, the two eyes of the same observer require a different amount of light to just discriminate the test-object. The minimum difference in this regard for the 15 observers employed was 0.12 meter-candle or 20 per cent. of the amount required for the better eye. Again, information is furnished upon the question of the superiority of binocular to monocular vision or seeing. The results indicate that "In 6 per cent. of the cases tested, the binocular result was equal to or approximated the result for the poorer eye; in 88 per cent. of the cases, it was better than the results of either eye; and in the remaining 6 per cent. of the cases it was intermediate to the results obtained with the two eyes separately. In none of the cases tested was it equal or approximately equal to the result for the better eye. In the 88 per cent. of cases referred to, less light was required for the discrimination of the test-object by the two eyes than by the better eye alone by amounts ranging from 14.5 to 67.3 per cent."

Various tests showed that, just as acuity increases slowly with increase of illumination, so also does it increase slowly with increase of sensitivity to light. Experiments upon the decrease in the amount of light required to just discriminate the test-object as the result of dark adaptation showed that the greater part of the observers reached their maximum acuity at the end of 15 minutes adaptation and that some even show a lower acuity if the series is continued beyond this time. This loss the authors believe to be due to the fatigue of the muscles of adjustment.

Sensitivity of the Apparatus for Detecting Small Errors in Refraction and in their Correction.

The remainder of the article consists of a discussion and presentation of results upon the fact that an eye suffering from an insufficient resolving power requires an increase in the amount of light required to just discriminate details in the standard acuity tests. For the purpose of demonstrating its sensitivity as a test principle, low astigmatisms and small errors in the amount and placement of astigmatic corrections have been chosen.

(1) *Sensitivity of apparatus for locating meridian of astigmatism.* It is obvious that if the eye has equal resolving power in all meridians the amount of light required to just discriminate the test-object will be the same in all meridians; if the resolving power is not equal, the amount of light required will be different in the different meridians. It was found that in case of an astigmatism produced by a 0.25 diopter cylinder an average result for 5 eyes shows that 107.2 per cent. more light was required for the discrimination of the test-object in the worst than in the best meridian; at 5 degrees from the best meridian, 50.0 per cent. more light was required; at 10 degrees, 95.5 per cent.; and at 45 degrees, 107.2 per cent.

Doubtless the apparatus can be used in different ways depending upon the experience and preference of the operator. For example, the minimum amount of light required to discriminate the test-object could be determined for one meridian and the setting of the light control be held constant while the test-object is rotated into different meridians, the observer being required to judge in each case whether more or less light would be required for its discrimination. This would serve as a rough indication whether or not the eye is astigmatic. The exact meridian of the defect could then be worked down through a series of settings of the test-card and light control. A more feasible method, at least in the more apparent cases, doubtless would be first to determine the region of the defect by means of other tests and use the present apparatus only for the more precise location of the meridian.

(2) *Sensitivity of the apparatus for detecting small errors in the placement of the correction of astigmatism.* It was found that in case of an astigmatism produced by a 0.25 diopter cylinder, a displacement of the correction 5 degrees from the true position required as an average result for the 5 eyes 66.5 per cent. more light than the true placement.

(3) *Sensitivity of the apparatus for detecting errors in the amount of correction of an astigmatism.* It is obvious that if the astigmatism is fully corrected the same amount of light will be required for the discrimination of the test-object in all meridians; if not, an unequal amount will be required in the different meridians.

An average result for the 5 eyes shows that in case of an error of 0.12 diopter in the correction, 54.6 per cent. more light was required in the worst than in the best meridian; in case of a 0.25 diopter error, 108.9 per cent. more light was required in the worst meridian; and in case of a 0.75 diopter error, 178.25 per cent. more light was required.

"In addition to the points already noted, the above results in connection with those of the preceding experiments emphasize the especial need of good resolving power for all work at low illuminations. A small error in refraction or in the amount and placement of its correction is a much more serious handicap at low than at full illumination. A correction, for example, which is adequate for all practical purposes at full illumination would in many cases raise the lower limit of clear vision to such a degree as seriously to disqualify the subject for work at low illuminations. It seems fair to infer too from these results that the individual differences in the amount of light required as a comfortable working minimum, frequently encountered by the illumination specialist, are due to differences in resolving power as well as to difference in retinal capacity."

(Abstracted from the *American Journal of Ophthalmology*, Vol. 3, pages 408-417. 1920.)

Eye Lesions Produced by Light Rich in Ultra-violet Rays—Senile Cataract, Senile Degeneration of Macula

Professor J. van der Hoeve

UNDUE exposure to light, either natural or artificial, is a factor in the causation of many disorders of the eye. According to Hertel every kind of ray can cause damage to the eye, if only the intensity is great enough. Of the different parts of the spectrum which can cause disease, the infra-red rays have been least studied. Vogt attributes to them the causation of glass workers' cataract. The visible rays are generally considered to be the cause of eclipse blindness. The effect of the ultra-violet rays on the eye is that which has been the most studied, especially in the last fifteen years.

In experiments it is very difficult to work with ultra-violet rays only and exclude all others; but it is far more difficult to distinguish the effects in natural light of light rays and ultra-violet rays. Hence it is better to speak of light rich in ultra-violet rays.

As to the parts of the eye which may be damaged by exposure to light of short wave-length, we find that scarcely any part of the eye is absolutely protected.

Not all the ultra-violet rays, which fall on the eye, are transmitted; the different media absorb a great part of them. Numerous experiments have been carried out to determine the absorptive capacity of the various structures of the eye for ultra-violet rays; and though the results are somewhat discordant, we know with certainty that the cornea and lens in particular partially absorb the ultra-violet rays.

Nearly all authors speak of the diminishing of rays in passing through a medium as having been caused by absorption. This is not correct; there are other causes besides absorption that make the media partially impenetrable.

According to Parsons the researches on this subject by Martin are the most accurate hitherto published. Martin's experiments show us that the cornea absorbs all rays beyond 295 $\mu\mu$ completely and has no absorptive capacity of rays of greater wave-length; whereas the lens completely absorbs all rays beyond 350 $\mu\mu$. The line is not a sharp one, absorption commencing about 400 $\mu\mu$. Tho Parsons is very absolute on this point, one must bear in mind that experiments of Hallauer, Birch-Hirschfeld, Schanz and Stockhausen and others showed that the absorption of the lens has many individual differences, connected with eye, constitution, and other not exactly determined influences, thickness, color, and consistency of the lens.

Whereas there are lenses which beyond 400 $\mu\mu$ absorb completely, Hallauer found youthful lenses which transmitted rays of 310–330 $\mu\mu$, and Schanz a juvenile lens, which transmitted rays from 300 $\mu\mu$ upwards.

From these results, we know that, when ultra-violet rays fall on our eyes:

1. The surface is reached by rays of every possible wave-length.

2. Iris and lens by rays from 295 $\mu\mu$ upwards, the retina as a rule only by rays from 350 $\mu\mu$ upwards; in some cases from 300 $\mu\mu$, in others 400 $\mu\mu$ upwards.

To discover what damage light, rich in ultra-violet rays, causes to the different parts of the eye, we may follow two methods, viz: to find from literature what affections of the human eye have been caused by such light, and to experiment on animals.

As a typical instance of the effect of natural light rich in ultra-violet rays on the human eye there is the well-known snow-blindness. As sources of artificial light of this kind, which can damage the eye, arc lamps, mercury-vapor, electric-welding, short circuit flashes are noted. The changes by lightning are attributed to other causes.

The first affection which human eyes suffer from natural and artificial sources of light rich in ultra-violet rays is photophthalmia, a name given by Parsons to these inflammatory conditions of the superficial part of the eye that are produced by exposure to various forms of bright light. In general, it is characterized by intense photophobia and lacrimation, with often blepharospasm and ciliary neuralgia. There is acute conjunctivitis and in the severest cases the cornea and iris may be implicated in the inflammation.

As a rule we attribute this inflammation of the superficial parts of the eye to the shorter waved radiation, whereas the affection of the inner eye is caused by the longer waved ultra-violet rays and the light rays. The difference is probably the cause of the two different kinds of snow-blindness that we distinguish (Wagenmann): one with preponderance of the external diseases of the eye, the other with preponderance of the internal diseases of the eye, which may be found separate or together, according to the presence of ultra-violet rays of shorter or longer wave-length or of both.

We find described as being caused by light sources rich in ultra-violet rays:

Photophobia, lacrimation, ciliary neuralgia.

Of the *eyelids:* erythema, spasm, edema.

Of the *conjunctiva:* changes of the epithelium, hyperemia, edema, chemosis, ecchymosis, injection, inflammation.

Of the *cornea:* haziness, opacities, infiltrations, ulcer.

Of the *iris:* hyperemia, change of color, pupillary contraction, inflammation.

Of the *ciliary body:* tenderness of the ciliary region.

Of the *disc:* hyperemia, inflammation, paleness of the temporal part.

Of the *retina:* scotoma, especially central scotoma, whitish spots at the macula, chorio-retinal changes, constriction of retinal arteries, dilatation of the veins.

We know that in sunlight and in diffuse daylight many ultra-violet rays are present, especially those of a wave-length between 300 and 400$\mu\mu$. Moreover, in the last twenty-five years the range of rays emitted by our artificial lights contain more ultra-violet rays than formerly. Consequently during the whole day, at least as long as our eyes are opened, they are irradiated by light rich in ultra-violet rays (sunlight, diffuse daylight, artificial light), therefore the fear is justified that this may damage our eyes.

If daylight can damage the eye, the next question is, Which affection can be caused? Dr. D. Neuman, of Nome, Alaska, found very many among Eskimos suffering from snow-blindness, chorio-retinitis, which according to Daland might be caused by the ultra-violet rays. The Eskimos, according to Daland, show conjunctivitis, cataract, trachoma, and snow-blindness as "common ocular diseases." The conjunctivitis and snow-blindness may be caused by the ultra-violet rays; with regard to cataract it is an open question whether it can be caused by ultra-violet rays.

Hess, who thinks we have up to now insufficient evidence to conclude that ordinary daylight damages the sound or diseased eye, writes: "But from general biological motives I could not readily conclude that in a living organ which has developed phylogenetically under the constant influence of daylight, the inconvenient peculiarity has developed itself of being seriously damaged by this same daylight."

So, though we agree fully with Hess, that exact statistics composed from uniform points of view on the relative frequency of senile cataract in different countries will be of high interest, and will probably answer the question, we must point out that the facts now known show plainly that senile cataract is more frequent and appears earlier in regions and countries which are more exposed to light rich in ultraviolet rays, and in people who expose themselves to this light.

We must also remember that even if light is a factor in the origin of cataract it is only one of a great many factors, which act on the whole organism or on the eye alone; that light is a principal factor in the origin of senile cataract is, however, highly probable. If this is true, the next question is: How is it possible that light, rich in ultra-violet rays, damages the lens so that senile cataract ensues?

Every attempt to explain the cause of senile lens opacity by the immediate influence of light, rich in ultra-violet rays, fails because those rays only reach the lens in the pupillary part of the lens, and the senile cataract does not begin at that place. Therefore, for the explanation of the connection between senile cataract and lighting we have to accept, next to the direct damage of the lens, an indirect one. When we look for some cause of indirect injury of the lens our thoughts turn to the ciliary body on which the lens is dependent for its nutrition; very little disturbance of the ciliary processes only is necessary to cause changes in the lens.

That the ciliary body can be damaged and even seriously damaged by light, rich in ultra-violet rays, is a fact. In snow-blindness the ciliary region shows tenderness, when we touch it, and the patients suffer from severe ciliary neuralgia. In ophthalmia electrica we find the same symptoms.

In the lens it seems a most illogical quality to be optically heterogeneous; not only because the diffused light is not used for the image on the retina but because it is also diffusely spread through the whole eye, so that the image in the retina may be blurred. It seems so irrational, that even well-known physiologists consider it axiomatic that the lens is optically empty. Notwithstanding this, the lens is optically heterogeneous.

Optically heterogeneity is known to everyone because we find in nature scarcely any substances which are optically homogeneous. It is best known by the fact that a sunbeam falling through a narrow slit into a dusty room can be seen from every side, because every particle on which the light falls, spreads the light on all sides, so that the track of the light is mapped out by the brilliant illumination of the dust or motes that are always present in a room.

To prove therefore that the lens is optically heterogeneous or homogeneous, we must distinguish fluorescent light from diffuse light. As we know, fluorescence is the quality of a substance that every part of the substance becomes, if light falls on it, a source of light itself which spreads the light on every side. In contrast to diffuse light the wave-length of the fluorescent light is different from the wave-length of the light which causes the fluorescence. Most substances follow Stoke's rule that the wave-length is increased by fluorescence; some other substances on the contrary diminish the wave-length of the light.

It is a well-known fact that the lens shows a very strong fluorescence, which follows Stokes' rule and increases the wave-length of ultra-violet, violet, and blue rays to a whitish blue. A great difference between diffuse light and fluorescent light is that diffused light is partly polarized, fluorescent light is always natural light, at least in substances which are not birefringent.

The third part strikes the ciliary processes at their most vulnerable point, the fully unprotected epithelium. If the lens is traversed by light in its sagittal axis a considerable amount of light is diffused sideways, that is, in the direction of the ciliary processes. Now we must bear in mind that a much greater part of dark ultra-violet rays is thrown in the same direction; so that by the optical heterogeneity of the lens the ciliary processes are illuminated by light very rich in ultra-violet rays. This fact can have as a consequence that, if intense light strikes the eye as was the case in the experiment of Birch-Hirchfeld, the ciliary processes may be seriously damaged; as Birch-Hirchfeld observed desquamation and swelling of the epithelial cells, hyperemia, hemorrhages, fibrinous exudation in anterior and posterior chamber. The posterior layer of the iris is struck by more rays than the ciliary processes, but it is far less vulnerable. Notwithstanding, Birch-Hirchfeld observed distinct damage of this layer and even the anterior part of the choroid was very hyperemic.

Thus optical heterogeneity can explain how the ciliary body, though well hidden, becomes inflamed; and how the pain may arise in snow-blindness and ophthalmia electrica, on touching the ciliary regions; and perhaps it is also responsible for the ciliary neuralgia which bothers the patient so much.

If the ultra-violet rays are less in number and the light which strikes our eye is not so intense, as for instance, daylight and the artificial light we use, no inflammation will occur; but the continual everlasting radiation of the few ultra-violet rays in the ciliary processes, will be able in the lapse of years to cause small changes in the epithelial cells, so that the secretion is changed a little. Even a very trifling alteration of the aqueous is sufficient to cause malnutrition of the lens; which may, in the course of fifty years and more, lead to obscuration of the lens and to senile cataract.

The above mentioned experiments of Parsons, Henderson, and Martin proved that the secretion of aqueous by the ciliary epithelium can be interfered with by radiation with light, rich in ultra-violet rays. Peters established the theory that many cataracts find their origin in small changes of the ciliary epithelium, so that the secretions and consequently the osmotic pressure of the aqueous is altered. In many cases he could find by microscopic examination lesions of the ciliary epithelium. I believe, that changes of the ciliary epithelium, requisite to alter the secretion of aqueous so that senile cataract ensues, may be so small that it is not possible to find them in every case of senile cataract, even by careful microscopic examination. It is possible that changes are so small that they escape our examination but are sufficient to change the aqueous humor and the nutrition of the lens.

In this way we can explain the acute inflammation of the apparently well protected ciliary processes by irradiation of light, rich in ultra-violet rays, the senile cataract, the observations of Hirchberg, Grosz, Schwitzer, Schulek, Daland, Walter, Ascher, etc., that senile cataract is more frequent and comes earlier in regions and countries which are more exposed to light rich in ultra-violet rays, and in people who expose themselves more than others to such light. Until now every theory that attempted to explain the connection between radiation and senile cataract went astray, because the rays work on the pupillary part of the lens (where they can cause opacities and epithelial changes), whereas senile cataract begins as a rule in the periphery.

Schanz, who established the theory that the ultra-violet rays change the soluble albumins of the lens into less soluble ones, and cause in this way opacities, uses the internal diffusion to explain how the whole lens can be obscured. But even when this is granted it is not yet explained why the senile cataract does not begin in the pupillary part of the lens, which in this theory must also be the case. In my theory the cataract may begin anywhere in the lens where the malnutrition of the lens has the greatest influence or where a locus minoris resistentiae is present.

If the lens diffuses light it is not the ciliary processes which get the most of the ultra-violet rays; the inner layer of the iris will get more and the pupillary part of the iris will get most; this is directly struck by the incident rays, and from behind by the rays reflected by the lens, and by those which the lens diffuses; whereas the posterior layer of the iris only gets diffused rays.

When the diffusion of the lens is so strong that cataract ensues, it is probable that the pupillary part of the iris, and perhaps even the posterior layer of the iris will suffer, too, from the radiation of rays of short wave-length, though they are much more resistant than the ciliary epithelium.

Have we any evidence in literature about the alteration of the iris in cataractous eyes? Yes; Lindberg found that, in eyes with senile cataract, at the pupillary border depigmentations and gaps were very often to be found. This is not a casual coincidence, nor are they both senile symptoms, for those same alterations at the pupillary border cannot be found in old people without cataract.

Hence there is according to Lindberg a connection between senile cataract and pupillary alterations. He was unable to examine sufficient patients giving useful results with diascleral transillumination, to decide whether there is also a connection between affection of the posterior layer of the iris and senile cataract; but most of the cases which he examined showed such a connection plainly. We see that the observations of Lindberg give just what we should expect if the theory above established is right.

Some time ago, when the possible effect of ultra-violet rays was very much overrated it was proposed to make our windows of protecting yellow-green glass, to cover every artificial light with them and to wear goggles. Now-a-days, nobody, I think, will be so afraid of those rays as to condemn people continually to wear protecting goggles; and I think also that it is not at all necessary to protect our eyes continually. We must remember that to cause one of the above mentioned senile affections those continually working under such rays need fifty or more years; so that a little protection will be sufficient to bring it about that those affections do not show themselves dangerously in our lifetime.

Normal people, for instance, might wear one of the protecting kinds of goggles only when they are more than usually exposed to ultra-violet rays, *e.g.*, on sunny days at the shore, or on the river, or on strongly reflecting roads and places on ice and snowfields, in hunting in the fields, etc.

People who have to labor continually in the vicinity of lamps which irradiate many ultra-violet rays will do well to cover the light with one of the protecting glasses.

Quite another question is it for people such as astigmatics, myopes, etc., who are already obliged to wear spectacles. Though they are already protected by the usual glasses, it would be but little disagreeable to them to have their glasses a trifle tinted as Hallauer. This is not ugly; it does not discolor the objects one sees, and as we know from hunters, it makes vision rather better than worse, so that there is no reason to refuse a protection which will be enough to prevent the undue effect of ultra-violet rays.

In all this we must remember that though we may be convinced that light rich in ultra-violet rays is a principal factor in the origin of cataract and retinal degeneration, it is only one of the numerous factors which may have an influence on the origin of these diseases. That senile cataract proves to be often hereditary (Vogt) does not contradict our theory; because the heterogeneity of the lens, which so differs in individuals, may be more hereditary in one family than in another.

The main conclusions of this paper are:

1 The lens is optically heterogeneous.

2 Ultra-violet rays may seriously damage the retina and the ciliary processes as well by natural light (snow-blindness) as in artificial light or in experiments.

3 Senile cataract and senile degeneration of the macula exclude each other in a certain measure; if one of those affections is present the other is absent or less developed.

It is probable that:

1 The damage of the ciliary processes by light rich in ultra-violet rays is caused by the optical heterogeneity of

the lens, which disperses a part of the rays and especially the ultra-violet to the ciliary processes and in other directions.

2 A principal cause of the origin of senile cataract is the influence of light rich in ultra-violet rays, such as daylight, which causes the opacity by interfering with the nutrition of the lens, in damaging the ciliary processes by rays dispersed against their epithelium.

3 One of the principal causes for the appearance of senile macular degeneration is the influence of light rich in ultra-violet rays which has passed through the lens.

(Abstracted *verbatim et literatim* from *American Journal of Ophthalmology*, Vol. 3, March, pp. 178–194, 1920.)

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H. v. Helmholtz

Hermann Ludwig Ferdinand von Helmholtz

Born at Potsdam, August 13, 1821.

Became a surgeon in the army.

Announced the discovery of nerve cells in ganglia, 1842.

Professor of Physiology, Königsberg, 1849; Bonn, 1855; Heidelberg, 1858.

Professor of Physics, Berlin, 1871, and director of the Physico-technical Institute, Charlottenberg, 1887.

Investigations covered the whole field of science, including physiology, physiological optics, physiological acoustics, chemistry, mathematics, electricity and magnetism, meteorology and theoretical mechanics.

Read the famous paper on *The Conservation of Force* in 1847.

Invented the ophthalmoscope in 1851.

Wrote his great treatise on *Physiological Optics*, which appeared in three parts, 1856–66. This is the most important book on the physiology and physics of vision.

Wrote his work on *Sensations of Tone*, 1862, "which may well be termed the principia of physiological acoustics."

Studied electrical oscillations from 1869 to 1871 and announced the velocity of propagation of electromagnetic induction to be that of light.

Aided one of his pupils, Hertz, who finally gave an experimental demonstration of electromagnetic waves, upon which wireless telegraphy depends.

Died in Berlin, September 8, 1894.

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Quotations from the Writings of von Helmholtz

"Science, whose aim is to understand nature, must set out with the assurance that nature is understandable."

"The iron labor of conscious logical reasoning demands great perseverance and great caution; it moves on but slowly, and is rarely illuminated by brilliant flashes of genius. It knows little of that facility with which the most varied instances come thronging into the memory of the philologist or historian. Rather is it an essential condition of the methodical progress of mathematical reasoning that the mind should remain concentrated on a single point, undisturbed alike by collateral ideas on the one hand, and by wishes and hopes on the other, and moving on steadily in the direction it has deliberately chosen."

"He who seeks for immediate practical use in the pursuit of science may be reasonably sure that he will seek in vain. Complete knowledge and complete understanding of the action of the forces of nature and of the mind is the only thing that science can aim at. The individual investigator must find his reward in the joy of new discoveries . . . in the consciousness of having contributed to the growing capital of knowledge. . . . . Who could have imagined, when Galvini observed the twitching of the frog muscles as he brought various metals in contact with them, that eighty years later Europe would be overspun with wires which transmit messages from Madrid to St. Petersburgh with the rapidity of lightning, by means of the same principle whose first manifestations this anatomist then observed."

"The last decades of scientific development have led us to the recognition of a new universal law of all natural phenomena. . . . This law is the Law of the Conservation of Force, a term the meaning of which I must first explain. It is not absolutely new; for individual domains of natural phenomena it was enunciated by Newton and Daniel Bernoulli; and Rumford and Humphry Davy have recognized distinct features of its presence in the laws of heat. The possibility that it was of universal application was first stated by Mayer in 1842, while almost simultaneously with, and independently of him, Joule made a series of important and difficult experiments on the relation of heat to mechanical force, which supplied the chief points in which the comparison of the new theory with experience was still wanting. The law in question asserts, that the *quantity of force which can be brought into action in the whole of Nature is unchangeable*, and can neither be increased nor diminished."

The American Journal *of* Physiological Optics

von Helmholtz

Thomas C. Mendenhall, D. Sc., LL. D.

THE first two decades of the twentieth century have been rich in contributions to nearly every department of science. Many of them have been such as to appeal to the interest and imagination of the people generally and because of their presentation in a moreor less sensational form they have often, by their very brilliancy, destroyed that sensitiveness for relative values that is necessary in order to relate them properly to the long series of scientific discoveries in which they find their ancestry. In a group of active and capable scientific men under forty years of age, one may find a surprising amount of ignorance regarding both the work and the workers in science of the nineteenth century and expressions of mild incredulity will be the response to a declaration that in neither work nor workers has the twentieth century thus far produced anything comparable in rank with that of its predecessor.

The nineteenth century will ever be famous for the working out of two great generalizations upon which modern sciences, both biological and physical, rest. Their tremendous importance is not approached by anything which the twentieth century has brought forth, nor can it point to any such galaxy of genius as that including Darwin, Wallace, Pasteur, Helmholtz, Kelvin, Joule, and a few others. The extraordinary enlargement of the boundaries of human knowledge during the past one hundred years has made it impossible for one to enjoy even a bird's eye view of the whole field. Bacon took all knowledge for his *specialty*, and Humboldt, in his *Cosmos*, came near doing what Bacon threatened.

The last representative of this type of scholarship (and there can never be another) was Baron von Helmholtz, concerning whose work and personality the editor of this JOURNAL has asked me to write something.

Twenty-five years ago, not long after his death, the scientific societies of Washington held a joint meeting in commemoration of his life and work and on that occasion I presented at some length a review of his career with some account of his more important contributions to the various departments of human knowledge which had been enriched by his researches: (*Science*, February 7, 1896). From this I may be permitted to draw as freely as necessary to enable me to present, briefly, those phases of his work which may be especially interesting to readers of this JOURNAL.

Hermann Ludwig Ferdinand, Baron von Helmholtz was born at Potsdam on August 31, 1821. His father, a professor of literature in the gymnasium, his mother, a direct descendant of William Penn, he inherited from both a love of learning which, even in early youth, strongly impelled him toward the study of nature. The necessity for earning a living obliged him to enter a profession and selecting, naturally, that best calculated to offer opportunity for indulgence in his favorite pursuits, he became a doctor of medicine and entered the service of the government as an army surgeon. His thesis, written when twenty-one years of age, announced the important discovery of nerve cells in ganglia and from that time to the end of his life not a year passed without a contribution from his fertile brain to some department of science. At the age of twenty-six years he published a paper on the *Conservation of Energy*, perhaps the most important piece of work in his long career of half a century as a productive investigator. A copy of this paper was presented to Tyndall, who was then a student of Magnus in Berlin, by Du Bois-Reymond with the remark that it was the product of the "first head in Europe." In connection with subsequent researches in the same line it made him a member of that immortal trio—Joule, Thomson (Lord Kelvin) and Helmholtz—to whom the world is indebted for the most important and far-reaching generalization in physical science since the time of Newton.

From that moment his advancement in official station was notable and continuous up to the end of his life, as was, also, the recognition of his remarkable scientific attainments. He abandoned the army to become a professor in the University of Königsberg, thus placing himself amidst much more congenial surroundings, for he was never fitted for army life.

At the age of thirty years he invented the ophthalmoscope, an epoch-making addition to the resources of the ophthalmologist, the value of which can hardly be over-estimated. When the famous von Gräfe was shown the instrument and saw for the first time the fundus of the living human eye, with its optical disc and blood vessels, his face flushed with excitement and he cried, "Helmholtz has unfolded to us a new world." This invention originated in an attempt to show to his class the nature of the glow of reflected light often seen in the eyes of animals, such as the cat.

In 1855 promotion came to him by appointment to the chair of anatomy and physiology at Bonn, and again four years later in a call to the same professorship at the University of Heidelberg. In 1860 the Royal Society of London conferred distinction upon him by putting him in the small group of its foreign membership. He remained at Heidelberg for a dozen years, a period in many respects the most productive of his life. Here, in 1863, he published his great work on the *Sensations of Tone*, a monument of painstaking research which resulted in the solution of the most important outstanding problems in acoustics. Three years later was issued the first edition of his *Physiological Optics*, a work which needs no word of commendation in the columns of a journal which has added character and dignity to itself by borrowing its title. To Helmholtz, these volumes together with the results of other researches upon which he was continually engaged, brought still more fame and further promotion in the appointment to a professorship in natural philosophy at the University of Berlin as well as the award of the Copley Medal by the Royal Society of London, generally regarded as the highest distinction which it can bestow. In the same year the King of Prussia conferred upon him the "Order of Merit" in Science and Art, an evidence of royal favor which was followed ten years later by the grant of hereditary nobility by Emperor William I. In 1887 he became the first director of the Physico-Technical Institute which the German Government had founded at Charlottenberg, largely the result of his own recommendation and advice.

In 1891 the seventieth anniversary of his birth was celebrated at Berlin with great ceremony in which representatives of all parts of the German empire participated and the Emperor placed him at the head of the entire civil list—the "first civilian in Germany."

In connection with the Columbian Exposition at Chicago in 1893 there was held an International Electrical Congress which included in its membership the leading students of electricity in the world to the number of about one hundred and fifty. Of these there was a specially selected group, about twenty-five in all, of official delegates, appointed by and representing their respective governments. By the American Committee charged with the preliminary organization, von Helmholtz was invited to be the Honorary President of the Congress and he was subsequently appointed as the head of the official delegation representing Germany. These appointments brought him to the United States for a stay of several weeks in the summer and autumn of 1893, his first and only visit to America. He had been reluctant to undertake this journey and at first declined the presidency of the Congress which we had tendered him. The reversal of this decision was brought about by an interview with the Emperor, an account of which I had from Baroness von Helmholtz (who accompanied her husband on his visit to America), some of the details of which have already appeared in print, but in view of the events of the last half dozen years the story will bear repetition.

"The Kaiser sent for him," said the Baroness, "and addressed him, saying; 'Helmholtz, we are sending to America for this Exposition the best we have in manufactured articles, in machinery, in the products of our mines and our fields, and in the works of our artists, but we are most proud of the *men* we produce and we want to send the best examples we have, so you must go!' " Of course this was a command that must be obeyed, "And yet," said the Baroness with a flash of indignation in eye and voice, "do you know that von Helmholtz is pushed off of the sidewalk in Berlin almost every day by any little lieutenant in the army who happens to be passing!"

He was given a most enthusiastic reception and cordial welcome at Chicago, many members of the Congress having studied under him at Berlin or Heidelberg, and wherever he travelled in America there was generous recognition of his high scientific rank. On his way home he met with an accident on board the steamer and this accident was thought to have shortened his life. He died within a year on the 8th of September, 1894, "princes and peasants alike mourning his loss."

Limitations of space (and of time, its fourth dimension) forbid even a brief catalogue of Helmholtz's contributions to science, even those of the first order. In one respect he was without a rival in his generation. By universal acclaim he stood in the front rank of mathematicians, of physicists, of physiologists, and even the chemists claimed him for their own, while his great work on the origin of the sun's heat entitles him to a niche in the astronomer's Hall of Fame. As evidence of the great area over which his researches were esteemed of first importance, I recall an obituary notice in a widely known London Journal in which it was indexed under the heading "The Stage and Music"—where his name appeared accompanied only by that of Anton Rubenstein!

In person von Helmholtz was not above the average height of his race, and his weight was greater than that usually allotted to his inches. His head in size, and especially in shape, was a distinct disappointment to those who look for a direct relation between cranial form and dimensions and intellectual power. In this respect, however, he was far behind his famous English contemporary, Herbert Spencer. Though dignified, modest, and quiet almost to reticence, he possessed a remarkable charm of personality which was the delight of all who came in intimate contact with him. "In scientific discussion whether on his feet or with pen in hand there was a certain massiveness about his style and manner which was generally irresistible. In his attacks upon the region of the unknown he showed, perhaps, less brilliant strategy than one or two of his contemporaries, but he rarely, if ever, found himself obliged to conduct a retreat."

Of all the eulogies which appeared on the announcement of his death, perhaps the finest was a brief stanza in the London *Punch*, which not infrequently becomes serious on great occasions. Its reproduction just at this time seems eminently fitting, and it may well be substituted for some of the "hymns of hate" of which we have heard.

"What matters titles, Helmholtz is a name
That challenges alone the award of fame.
When Emperors, Kings, Pretenders, shadows all,
Leave not a dust trace on our whirling ball
Thy work, oh grave-eyed searcher, shall endure
Unmarred by faction, from low passion pure."

Ravenna, Ohio.

The Description of an Ophthalmoscope
Being a
Translation of the Original Essay by von Helmholtz

Thomas Hall Shastid, A.M., M.D., F.A.C.S.

[We are pleased to present to our readers this translation of the original essay of 1851 by von Helmholtz. This translation by Dr. Shastid is the first to be made into any language, and while it has been made available elsewhere (*The American Encyclopedia of Ophthalmology*) to many readers, its contents are unknown to most students of the eye. EDITOR.]

Introduction

THE present treatise contains the description of an optical instrument by which it is possible in the living to see and recognize exactly the retina itself and the images of luminous objects which are cast upon it.* The instrument has, for this purpose, two different problems to solve. First, everything which we can see of the background of the uninjured eye appears to us absolutely dark. The cause of this lies, as I will show, in the light-refracting media of the eye which, under ordinary circumstances, hinder us from seeing illuminated parts of the retina behind the pupil. Therefore, the first question is to discover a means of illumination whereby exactly that portion of the retina on which we gaze through the pupil may be adequately lighted. Secondly, we view the background of the eye only through the light-refracting media. These, however, cast images of the retinal

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*Even the ancients, as a matter of course, had noticed that the eyes of certain animals are brilliant in the dark. Thus Pliny (*Book XI*, Chap. 55): "The eyes of animals that see at night in the dark, cats for example, are shining and radiant, so much so that we cannot bear to gaze upon them; those of the she-goat, too, and the wolf are resplendent, and emit a light like fire." Pliny did not, however, attempt to explain the phenomenon.

In 1704, Jean Mery, of Paris, performed his famous experiment with a cat. Having immersed the animal in water, he first observed that the pupil dilated (as a result of suspended respiration) and then he beheld in all its glory the fundus of the animal's eye—the entrance of the optic nerve and all the colors and vessels of the choroid. Mery understood quite well enough that something more than mere pupillary dilatation was necessary to account for the possiblity of observing the objects, which, in general, do not lie for the observer within the limits of plain vision. We need, therefore, together with a proper procedure for illumination, also further optical expedients which will render possible for the observing eye a correct accommodation for the objects which it should see.

1 Illumination

In order to be able to find the essential conditions for the method of illumination, we must first of all make clear to ourselves why, as a rule, the ground of the eye behind the pupil appears to us to be of so deep a black.

The cause of this is not the condition of the pigment of the chorioidea; for, if the pigment layer absorbed the light which

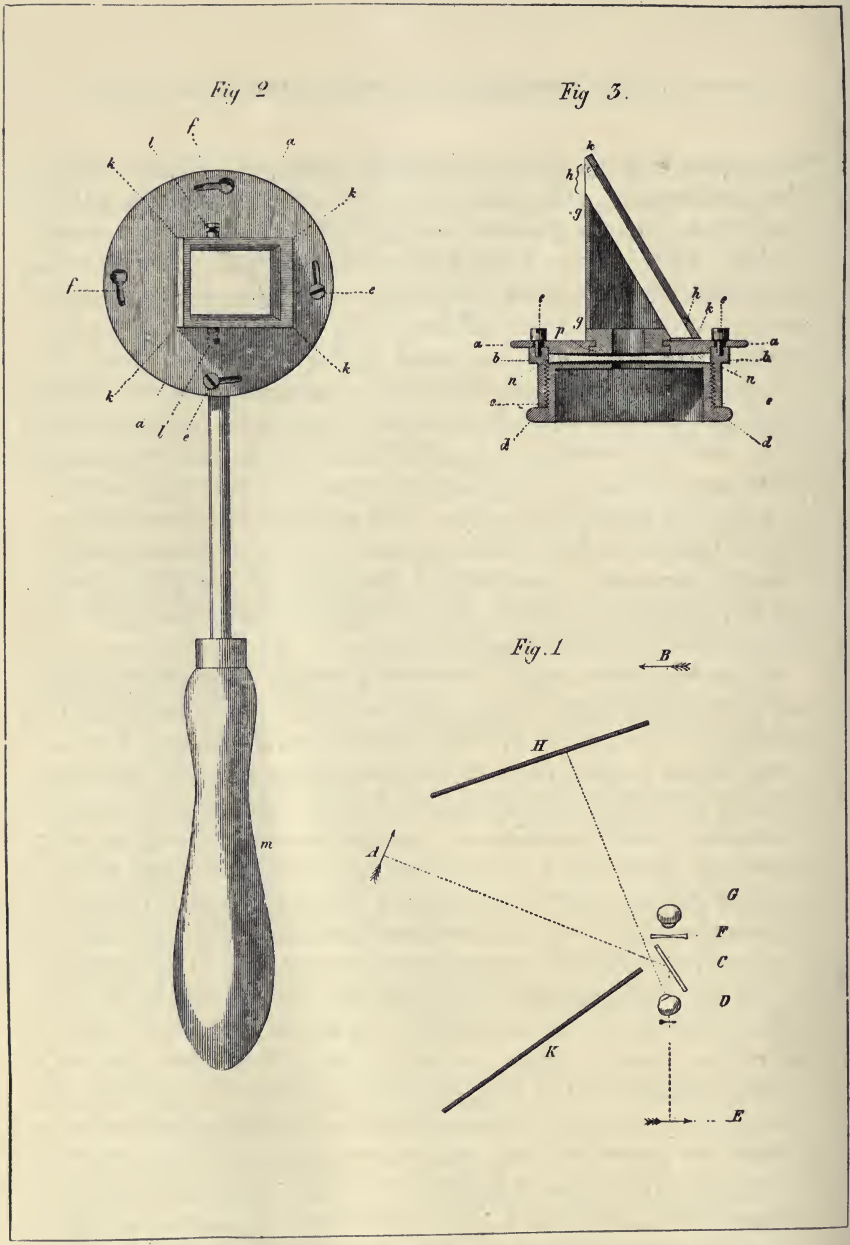
fundus of the eye when the eye was under water. His explanation, however, of the "something more" was wholly erroneous. He believed, that is to say, that the view of the fundus was rendered possible by the water's filling up a multitude of tiny "unevennesses" on the anterior surface of the cornea. Five years later, de la Hire stepped forward with the correct explanation. According to him the water obviated the refraction of light by the cornea, so that all rays leaving a given point upon the fundus emerged from the eye not as parallel, but as divergent, rays. De la Hire also observed, incidentally, that the disturbing light reflexes proceeding from a cornea *in aero* are done away with by the water.

In 1796 Fermin observed a certain luminosity in the pupils of an Ethiopian albino. In 1816 Scarpa remarked upon a similar phenomenon in a certain disease of the fundus, and, one year later, Beer described the same condition fully, inventing therefor the expression "amaurotic cat's eye"—a term which is still in use. In 1836 Hasenstein first produced a factitious luminosity by compressing the eyeball backward—making the eye, in fact, artificially hypermetropic. In 1847 Babbage, an English mathematician, exhibited to Wharton Jones, the distinguished London oculist, the model of an instrument invented by him for the purpose of examining the interior of the eye. It consisted of a small plane glass mirror, from which a portion of the silvering had been removed. This device, however, was first made known to the world in 1854, by Wharton Jones (*Brit. and For. Medico-Chir. Review*, Oct., 1854). The services of Brücke (in 1845, published in 1847) and of Cumming (in 1846) are adverted to herein by Helmholtz.

The earliest reception of the ophthalmoscope is decidedly interesting. Thus, to quote from Koenigsberger, "*Hermann von Helmholtz*," (1906) p. 74: "The ophthalmoscope was, however, some time in making its way, on account of the mathematical and physical knowledge presupposed by the '*Description of an Ophthalmoscope for the Investigation of the Retina in the Living Eye*,' published in the autumn of 1851, and people were at first very shy of employing it. One distinguished surgical colleague told Helmholtz he should never use the instrument—it would be too dangerous to admit the naked light into a diseased eye; another was of opinion that the mirror might be of service to oculists with defective eyesight—he himself had good eyes and wanted none of it"—(T. H. S.)

falls upon it even more completely than any other known black substance, still, there lie before the chorioidea parts which can reflect a quantity of light sufficient to render them visible. That is true, first of all, of the substance of the retina which, to be sure, in the recent condition, is very transparent, and marks itself off but little against the dark pigmentary background; to a much higher degree, however, it is true of the blood vessels of this membrane, whose tiny stems carry blood enough to exhibit a strongly red hue. Finally, there appears, even in the fundus of the eye, a shining white spot; namely, the place of entrance of the optic nerve, on which no pigment at all lies, and which, therefore, reflects all the light that falls upon it. And yet we observe, under ordinary circumstances, behind the pupil of the living eye, not the slightest trace of the red color of the blood, nor of the white color of the optic nerve.

It can be shown much better by a simple experiment that not the color of the background but only the refraction of the light in the ocular media is the cause of the deep blackening of the pupil. Let one take any kind of small camera obscura well blackened within, and let him bring to the place where the picture is produced an opaque white card, for example one from thick white drawing-paper. Among other kinds of camera may be employed the ocular tubes of most microscopes, after the ocular glass has been removed therefrom, and the collective glass has been inserted. These tubes are, as a rule, precisely as long as the focal distance of the collective glass. If one sets them with the end which contains the ocular upward upon the white card, then they form a camera obscura of the kind we need. There are thrown, in this case, very bright images of the surrounding illuminated objects, on the white card, and still the interior of the instrument, when one looks into the lens in any desired direction, appears absolutely black. We have here a *facsimile* of the eye, where cornea and crystalline lens are substituted by the objective lens of the camera, and the retina by a clear white



Photographic reproduction (actual size) of the original illustration in Helmholtz's *Beschreibung eines Augenspiegels.*

paper surface, but there occurs apparently the same complete darkness of the internal space as in the eye, as long as the paper surface lies precisely at the spot where the tiny images of external objects are produced. If one takes away the convex glass, or if one materially alters its distance from the paper surface, there appears to the beholder at once the clear white surface of the paper.

How, now, can the refraction of the light produce the phenomenon described? Let us consider the course which the rays of light must take, according to the physical laws of the refraction of light in the eye.

Let light fall from a luminous point upon a fittingly adapted eye, concerning which we assume that it is formed with absolute accuracy, that is that all the incident rays from the point in question concentre upon a single point of the retina. Of the light which, by the ocular media, is caused to converge upon this membrane, the greater part is absorbed by the black pigment, while the smaller is reflected partly by the nerve elements and blood vessels, partly by the layer of rod-shaped corpuscles. That which is thrown back by the latter structures passes, as E. Brücke has shown, back out through the pupil, without becoming scattered to any other portion of the wall of the eye. In this way is avoided the spreading of perceptible quantities of dispersed light within the eye. The reflected rays, which, from the point of convergence on the retina pass back out divergently to the refracting surfaces of the eye, follow then precisely the same path, in a reverse direction, by which the incident rays of the luminous point converged from the refracting surfaces of the eye until they reached the retina. From this it follows that the returning rays, even after they have passed clear through the refractive media and out of the eye, must coincide completely with the incident rays, and must therefore finally all betake themselves to the original luminous point.

For, when two rays, which pass through several simply refracting media in a reverse direction, coincide in one of the same [media] they must do the same in all [the media]. On the limiting surfaces of the medium, that is to say, within which they coincide, the angle of incidence of the outcoming rays is identical with the angle of refraction of those which are entering. As now, according to the laws of refraction, the proportion of the sine between the angle of incidence and the angle of refraction of the former, is precisely as large as that between the angle of refraction and the angle of incidence of the latter, so must also, on the other side of the refracting surface, the angle of refraction of the outcoming and the angle of incidence of the ingoing rays, be equal. As, at the same time, all these rays lie in one plane, the plane of refraction, it follows that they also fall into one another [coincide] in the second medium. In like manner it follows further for the third, fourth medium, and so on.

Let us apply that to the case where any given system of refracting surfaces produces an exact image of the luminous point *a* at the point *b*, that is where all the rays which proceed from *a* unite again in *b;* then follows the well-known fact that in this case, always, *a* will be the image of *b*, if the latter sends out rays. Exactly upon the same paths, that is to say, on which rays from *a* proceed to *b*, they may also return from *b* to *a*. If now *a* is a luminous point outside the eye, and *b* its image, a point on the retina, then the ocular media will concentrate the returning light precisely at *a* into an image of *b*. The image of the illuminated retinal point will coincide exactly with the original point of luminosity. The same is still valid, also, when we have to do not with a luminous point, but with a luminous surface or a body, as soon as the eye is adapted for its outlines. All the incident light which is thrown back can always only return to its place of origin, and never can proceed in any other direction.

From this it follows that, without special expedients, we can see nothing of the illuminated portion of the retina, because we cannot bring our eye into the direction of the returning light without at the same time cutting off the incident light absolutely. To our pupil no light from the depths of the other's eye can return which has not proceeded from it (*i. e.*, our pupil). And as, in general, none at all has proceeded from our pupil, it sees in the darkness of the other's eye merely the reflection of its own blackness; only those portions of the retina become visible to it on which its own dark image is copied.

We have until now assumed that the observed eye furnishes absolutely accurate images. When that is not the case, the propositions heretofore laid down do not hold strictly true, the returning light will indeed proceed to the illuminating body, but it will also in part pass by that, and an observer who approximates himself to the line of direction of the incident light will be able to perceive a part of the light which is coming out. On this fact are based the methods of Cumming (*Medic. Chirurg. Transactions*, Vol. 29, p. 284) and Brücke (*J. Müllers Archiv.* 1847, p. 225) for observing the illumination of human eyes. From what has been said it is manifest that, in this way, the illumination must be greater, the less exactly the rays of a luminous point are concentrated on a point of the retina, therefore especially in faulty adaptation. Besides, I have convinced myself that one may observe a weak illumination, according to the method of E. Brücke, even in eyes with good acuity and under perfect adaptation for the luminous body, from which is to be concluded that, under all circumstances, a small quantity of incident light is scattered laterally. The cause thereof may be inexactness of the eye, incomplete transparency of its refracting parts, or diffraction at the border of the pupil.

In any case, the observer perceives, in this experiment, only a small part of the returning light, and indeed precisely that which is irregularly refracted and which cannot be used for the production of a regular image. Some other method is necessary for the attainment of our object, a method which makes it possible to look into the eye not merely somewhat, but exactly, in the direction of the incident light. The expedient for this has already been found in an accidental observation by E. Brücke. v. Erlach, who wore spectacles, saw, indeed, the eyes of an acquaintance shine, when the acquaintance saw reflected in the lenses of the spectacles a light which there was in the room. In this way, therefore, uncovered lenses were employed as illuminating mirrors, and through these very objects the observer looked toward the observed eye. Precisely the same expedient we shall employ for our purpose, replacing, however, the spectacle lenses to advantage by well ground plane glasses.

In a darkened room, where only a single source of light, a well burning lamp or an opening in the window shutter for the sunlight, is present, let one set a small, plane glass plate in such a way that the observed eye may perceive therein the mirrored image of the light, without, however, its necessarily gazing at this mirrored image directly. From out the anterior surface of the lens there falls, by this arrangement, light into the observed eye, and through the same glass at the same time the observer can view the eye without, while so doing, being in the least aware of any light which is being reflected from its anterior surface. One sees that, in this way, it becomes possible to look into the subject's eye in precisely the same direction as that in which the light falls upon it. Under these circumstances the eye of the observer in fact receives light from out the depths of the other eye, and sees its pupil apparently grow luminous.

In Fig. 1, let A be the flame, C the glass plate, D the observed, G the observing eye. The light from A which falls upon the mirroring plate is by that partly reflected, and the reflected part continues, according to the laws of catoptrics, as if it proceeded from the reflected image of the flame at B. For the observed eye this mirrored image represents the place of the luminous object, and upon its retina is thrown an inverted and minified image. Moreover, the axis of this eye can be turned in any direction, say toward the object H. According to the already developed rules, the refractive media of D cast the image of its retina and of its retinal images again at B. For B is the apparently present object for the eye D, and the rays returning from D must proceed again to their place of origin. On the way from D to B this light encounters once more the reflecting plate, a part is reflected and returns to the real flame A, another portion passes through the glass and strikes the eye of the observer G.

By this arrangement the pupil of the eye D appears to shine with a red light, and indeed as a rule more strongly than I have seen it do by Brücke's method. According to that method, there contributes to the illumination only the little light which, in the eye, is not completely and regularly refracted; according to the method just described, on the contrary, the entire light, with the exception of the part (to be sure not an inconsiderable part) which is lost by the passage through the reflecting glass. Moreover, the illumination is of very different strengths, when different portions of the retina receive the image of the flame. When the eye D turns in different directions, the clear retinal image must always remain in the prolongation of the line B D, and will therefore fall successively on various portions of the background. If it falls on the place of entrance of the optic nerve, then the most of the light is reflected, the pupil lights up with a strong yellowish white, almost as if the flame stood behind it. The retina proper, on the other hand, reflects less, and indeed red light. In general, the image of the flame upon it appears the brighter, the nearer; the darker, the farther it lies from the place of entrance of the optic nerve. On the contrary, the place of direct vision, the yellow spot (which is struck when the observed eye D gazes directly at the mirrored image of the flame at B) reflects, by way of exception, very much less light than the parts which are nearest to it, and is therefore the most unfavorable spot for this experiment.

In order to fulfill the condition that the observer gaze into the eye exactly in the direction of the incident light, the glass plate may be directed either by the observed or by the observer. If the former is to do it, let him turn the plate first of all so that he sees therein the mirrored image of the light, then again so that this image appears to him exactly in the same direction as the observing eye, that, in other words, the latter and the mirrored flame cover each other. In this way the required condition is fulfilled. At the same time occurs this inconvenience, that the observed eye must look directly at the flame, the retinal image therefore falling precisely on the spot whence the light is the least reflected. If, however, the observed eye, after it has found the correct position, turns a little sidewise, in order to let the light shine more brightly, then the pupil becomes displaced and the correct position is disturbed. Still, one can then assist the matter by gentle turning of the mirror now this way and now that.

It is better, however, to perform the experiment in another way, whereby the observer holds the glass himself. One must, by this method, shade the face that is being observed, and make the reflecting plate so small that it is barely large enough to see through. The light reflected from it then produces on the shaded face of the observed a small, bright spot, which has about the form of the reflecting glass. This point should be so managed by the observer that its centre falls upon the observed eye, while he himself looks through the glass. In this way the glass may easily be placed correctly, and the observed eye may, without the slightest difficulty, be turned toward all sides in order to cause the image of the flame to fall on different parts of the retina.

Every person can, furthermore, in similar fashion, by the aid of a bit of plane glass, see one of his own eyes grow luminous. He should step before a mirror, set up a lamp at one side, hold the glass before his right eye in such a way that he sees the flame reflected in the plate, and turn the glass so that the image of the flame coincides with the mirrored image of his left eye; then the left eye sees the mirrored image of his right pupil grow luminous, but of course only weakly so, because the retinal image falls on the outer side of the eye at a considerable distance from the optic nerve.

Moreover, the same simple expedient permits itself to be employed with advantage for illumination, in every instance when one wishes to look into a dark cavity with a narrow opening, for example, the auditory meatus, the nose, and so on. In order to view the drum membrane, one should seat the subject of the experiment with his back toward the window, preferably in sunshine, draw the auricle a little downward, and cast the reflected sunlight into the auditory meatus, while one gazes through the glass. In this way one may very easily and conveniently illuminate the tympanic membrane as strongly as he wishes, and so observe it.

In order to see the pupil become luminous, any simple plate of glass suffices for the mirror; one does not need in that case to pay particular attention to the intensity of the light. Should it be desired, however, by means of this light to recognize distinctly the structure of the retina and the character of the image of the flame, then one must endeavor to make the illumination as strong as possible. That can be done in two ways, namely; by a proper choice of the angle under which the incident light is reflected from the mirroring plane, and by an increase in the number of the reflecting plates. I will now unfold the principles which have guided me in this connection during the construction of my instrument, and which would also serve as a basis should oculists think it necessary to produce modifications of the instrument for practical purposes. For those of my readers to whom the physical conceptions involved are not familiar, I remark furthermore that this exposition is not necessary for an understanding of the sections to follow.

From every limiting surface of a glass plate, the more light is reflected the larger the angle of incidence, that is, the angle between the ray and a line which stands vertical to the plate. Since, in the case of reflection from the upper surfaces of transparent bodies, the light waves of different undulatory directions conduct themselves differently, we must think of the incident light as divided into two equal parts, of which the one is polarized parallelly to the reflecting surface, the other vertically thereto. The light-intensity of all the incident light we will call J therefore, that of each of the two divisions mentioned ½J, the angle of incidence (angle between the incident ray and the incident-perpendicular) a, the angle of refraction (between the refracted ray and the incident-perpendicular) a_1, the index of refraction n. If a is given, we find first of all a_1 by means of the equation

$$\sin. a = n \sin. a_1$$

The intensity P of the light reflected from a limiting surface between air and glass and polarized vertically to the plane of incidence, is, according to the formula of Fresnel

$$P = \frac{J}{2} \cdot \frac{\tan g^2 (a - a_1)}{\tan g^2 (a + a_1)}$$

Likewise the intensity Q of the reflected light which is polarized parallelly to the plane of incidence

$$Q = \frac{J}{2} \cdot \frac{\sin^2 (a - a_1)}{\sin^2 (a + a_1)}$$

When several reflecting plates lie parallel, one behind another, and the illuminating surface is sufficiently large for its mirrored images, which are produced by the individual reflecting surfaces, to superimpose themselves, in greatest part, for the observed eye, then the individual images combine into one image of greater brightness. By computation of the quantities of light reflected to and fro between the different surfaces, one is able to determine for every system of parallel surfaces, how much light is, on the whole, reflected. For an indefinite number n of the reflecting surfaces one finds the sum of Π of the light polarized vertically upon the plane of incidence

$$\Pi = \frac{nP}{J + 2(n-1)\,P}\,J$$

and the sum Σ of that which is polarized parallelly to the plane of incidence

$$\Sigma = \frac{nQ}{J + 2\,(n-1)\,Q}\,J$$

As I find these formulae in no writing on physics I give their derivation briefly at the end of this essay. (See *Appendix.*)

The sum $\Pi + \Sigma$ gives us the entire quantity of light which is thrown back from the system of reflecting surfaces and which proceeds to the observed eye. We will set it down as equal to H, so that

$$H = \Pi + \Sigma$$

When the width of the pupil remains unchanged, the brightness of the retinal image is proportional to this quantity of light. The quantity of light returning from the eye we may therefore set down as equal to m H, where *m* designates a coefficient whose value is constant for different light-intensities, though dependent on the nature of the place on the retina from which the light proceeds. The returning light divides at the reflecting surfaces once more into a reflected and a transmitted portion, only the latter arriving in the observer's eye. The light which is reflected at the retina possesses, as is generally the case with diffuse reflected light, no longer any polarization, conducting itself in this respect, therefore, like the light from the light-source as it strikes upon the mirror. Inasmuch as, in addition, it falls upon the plates under the same angle, proportionately as much of it is reflected and transmitted as of the former (the light from the light-source). If we designate the transmitted part by X, then we have the proportion

$$X : m H = (J - H) : J$$

From this may be computed the quantity of light X, which passes into the eye of the observer. For $H = 0$ and $H = J$; that is, when no light or all the light is reflected, X will $= 0$. Between these extreme values of H exists a maximum of the value of X, which can be computed according to the known rules of the differential calculus. The maximum occurs when

$$H = \tfrac{1}{2} J$$

Then will

$$X = \tfrac{1}{4} m J$$

By this condition is also determined for a given number of reflecting plates the angle under which the reflection must occur in order to give to the observer the brightest image. Unfortunately, the equation which expresses the dependence of the value H on the angle of incidence a, cannot be solved after a; we can therefore find the proper values of a only approximately by means of computational trials. Besides, it is of no use to drive the exactness of this computation very far, first, because the brightness for the observer is not materially altered, even when the position of the glasses is not that requisite for the maximum, and, secondly, because the alterations in the width of the pupil produced by different intensities of the incident light cannot be taken into account.

As the pupil of the observed eye becomes smaller under stronger incident light, the brightness of the retinal image will not increase entirely in the same proportion, when the values of H increase, as they should do according to the developed formulae. It is therefore more advantageous to re-establish in the instrument the values of H as somewhat smaller than would be requisite for the maximum of H in the foregoing computation. One reaches, for example, the value, which slightly deviates from the foregoing maximum,

$$X = 1/5 \, m J$$

when the light is reflected from one glass plate at an angle of about 70°, from three at an angle of 60°, of four at 55°, and these positions are therefore approximately the most advantageous.

The necessary brightness, therefore, can even be reached with a single glass plate for a mirror. The use of several plates at a smaller incidence-angle has, however, essential advantages if one would attain to distinct images of the retina. First of all, glass plates, even when they have well ground parallel surfaces, are not always internally of so homogeneous a structure as still to yield, by an oblique view, good, distinct images. Then it is more difficult, by a very oblique view, to give to a reflecting plate the correct position toward the observed eye, and to hold the plate therein. Also the observer, by the lateral parts of his head, cuts off more easily the rays of light which should fall upon the mirror; especially may this be avoided with difficulty when the angles of incidence are more than 70°. Finally, it remains to be especially considered that a small quantity of the light which falls into the observed eye is in fact reflected from its cornea and appears to the observer as a washed-out light spot in the visual field. This falls over the centre of the pupil, when the observed eye turns straight toward the mirror, therefore when it looks directly at the mirrored image of the flame; it falls more to one side when the observed eye gazes in any other direction, disturbing, however, the observation of the retina always more or less. It is therefore an essential advantage if one can weaken the corneal reflex for the observer to a considerable degree. Now, in fact, that image appears much weaker when 4 plates reflect at 56°, than when 3 reflect at 60° or one at 70°, while the retinal image, as already mentioned, holds to just about the same illumination. That is to say: the apparent brightness of the corneal reflex is not proportional to that of the retinal image, because the light which falls into the observed eye, and which is partly or wholly polarized by reflection, is depolarized by the diffuse reflection at the retina—something which does not occur from the specular reflection at the cornea. If the cornea, of the quantity of light A which falls upon it, reflects the portion μ A, then the quantity of light which, in our experiments, passes from the cornea into the eye of the observer, equals, according to the same principles and the same designation as before,

$$\frac{\mu\Pi\ (J-2\Pi)+\mu\Sigma\ (J-2\Sigma)}{J}$$

Computation gives the result already stated. It is therefore from every point of view more advantageous to attain the necessary brightness by increasing the number of the plates, while they reflect the light at the polarization angle of 56°, than by increasing the angle of incidence; indeed the corneal reflex could be made to disappear entirely by increasing very much the number of the plates.

I have assumed, in the foregoing explanations, that the flame of a good oil-lamp with a double draught is employed as the light-source. When the experiment is properly conducted, the light of such a lamp is not so strongly reflected as very much to dazzle or fatigue the lateral parts of the retina of the observed eye. One can therefore easily continue the experiments as long as one likes. Only when the eye looks directly at the mirrored image of the flame, will this degree of brightness be found not long endurable. If one has at his disposal a more intense light, for example sunlight, which falls into a dark room through an opening in the window shutter, then one can see the picture of the retina much brighter, if one, after proper weakening of the light, causes it to reflect from a mirroring-plate as vertically as possible, than when this takes place obliquely. The quantity of light which one may permit to enter into the eye is limited particularly by the sensitiveness of the latter. If, now, one has at his disposal excessively strong light, which by every kind of reflection, if it is not at the same time adequately weakened in another way, exceeds this limit, then the observer sees the retinal image, which has reached the limit of endurable intensity, at its brightest when as little as possible is lost at the second reflection. That is, however, the case when the light is thrown back from a plate almost vertically.

I have not had opportunity to institute such an investigation by means of sunlight; I do not believe, however, that, by that method, any considerable advantages are to be secured, because, in the case of vertical reflection, the apparent brightness of the disturbing corneal reflexes increases at a much higher rate than that of the retinal image.

There was expressed to me a number of times the supposition (at first blush a very plausible one) that, by a convex lens which should concentrate toward the observed eye all the light which falls upon it, the quantity of light falling into the eye and therefore also the brightness of the retinal image, could be considerably increased. I will therefore here direct attention to the fact that, in this way, not the brightness but only the size of the retinal image is increased. When we bring the eye to the point of union of the light-rays, which have passed through a lens, then the entire surface of the lens appears to us luminous with that light-intensity which belongs to the luminous point. Instead of the smaller retinal image of the luminous point, there is formed for us therefore a larger one with the same intensity, that of the lens surface. Moreover, by no complicated arrangement of lenses can the brightness be increased. In order to perceive this, we need only to remind ourselves of this fact from the theory of telescopes, that through no telescope or similiar arrangement of lenses can an object of appreciable diameter appear brighter than with the naked eye. As, now, the inhabitant of the seeing eye subjectively perceives the surface no brighter through the lenses, so can, objectively, the image in his eye by the use of no sort of lenses be brighter than without them. For to an objectively brighter retinal image there must always correspond a stronger subjective light-perception.

2 Production of a Distinct Image of the Retina

We now come to investigate how, by means of the light which, returning from the retina of the observed eye, falls into the eye of the observer, we may be able to receive distinct images of the retina itself, and of the picture of the light-source cast upon it. For this purpose let us take again our Fig. I. According to the explanations just made, the ocular media will so refract the rays returning from points of the retina of the eye D, that they come together outside the eye and indeed in the corresponding points of the image B. The image which the ocular media cast of the retina and of the retinal image of the flame, coincides therefore in size and position with the first reflected image of the flame. An observer who (reckoning outward from the mirror) stands on the other side of B and at the distance of distinct vision from B, would therefore in fact be able to see that image of retinal objects distinctly. His visual field, however, limited by the pupil of the observed eye, would, at the comparatively considerable distance of the two eyes from one another, be so small that it would be impossible to combine the viewed details into a complete picture.

The regard which we must pay to the enlargement of the visual field makes it much more necessary to approximate the two eyes as closely to each other as possible. Then, however, the image B falls in general behind the back of the observer, and cannot be plainly seen by him. If, for example, in Fig. 1, the observing eye is at G, then it receives the light rays which proceed out of the eye D and which come together at the points of B. Now a normal eye can indeed unite upon its retina parallel rays, as these move from infinity, and divergent, as these come from nearer points, but not convergent rays. The simplest way to assist in this matter, and to make the convergent bundles of rays divergent, is a concave lens, which is inserted between the mirror and the eye of the beholder, as in Fig. 1 at F.

According to the known laws of refraction in concave lenses, the convergent rays which strike upon F will, after their exit from the lens, either be less convergent (when, that is to say, the focal distance is greater than FB) or they become parallel (when the focal distance equals FB) or, finally, divergent, as if they came from points of an image E behind the observed eye (when the focal distance is smaller than BF). In the latter case the concave lens acts precisely as it does in opera glasses, where it likewise converts the inverted imperfect image, which the objective lens should cast at its focus, and which lies on the side of the observer, into one which stands upright and which appears to the observer to be on the other side of the glasses. In our case, likewise, the ocular media form the objective glass of a microscope, which is constructed on the principle of a Gallileonian telescope, while the concave lens represents the ocular.

If the accommodation distance of the two eyes DB and GE are given, and in addition the mutual distances of the eyes and the concave lens are settled according to the principles above set forth, that is, made as small as the mirror permits, then is the focal distance which is to be given to the concave lens to be determined according to the known laws of refraction in lenses. This is found to equal

$$\frac{EF\ \ BF}{EB}$$

or:

$$\frac{(EG-GF)\ (BD-DF)}{EG+BD-DG}$$

The greater are the accommodation distances EG and BD, the greater must also be the focal distance of F. The observer will, therefore, if one of the two eyes is short-sighted, employ stronger concave lenses, but, if one eye is far-sighted, weaker ones, than for two normal eyes. When the observing and the observed eye exchange their rôles, without altering the condition of their accommodation, there will generally become necessary a glass of a different focal distance, and indeed, as $GF < DF$, a weaker one, when the more short-sighted eye observes, than when it is observed. Still, a closer consideration of the foregoing formula shows that this difference is extremely slight in the case of not too short-sighted eyes, so that, in the case of such, the same glass can serve for mutual observation.

The magnification is determined according to the known laws of optics in this way, that the image E, viewed from the center of the lens F, must appear under the same visual angle as B, its imaginary object. Since the eye G, the lens F and the eye D stand as closely together as possible, then will B appear from F only a little larger than from D. The eye G therefore sees the retinal image of the flame magnified, and indeed just as large, or, considered exactly, a trifle larger, then the eye D sees the original flame. The parts of the retina on which the image of the flame falls, appear likewise in the image E, again magnified, of course, in the same proportion as that.

According to what has just been said, the proportion of this enlargement is equal to that of the retinal image to its object. Let us take as the distance of the decussation-point of the refracted rays from the retina, according to Volkmann's measurings, 4 lines; for the distance of the object from the eye the normal visual distance of 8 inches; then the magnification is found to be 24 times.

We have compared the ocular media in our experiment with the objective of a microscope, the concave glass with the ocular. Now, in place of the latter, one should be able to produce a combination of two convex lenses, which stand at a distance from one another of less than the sum of their focal distances, as is the case in the ordinary compound microscope. The first of the lenses would, like the collective glass of this instrument, unite the weakly converging light-rays which proceed from the observed eye, more promptly to an image, which, situated between the lens and its focal distance, would exhibit the flame-image upright, the retina inverted. This image could then be seen magnified by the second convex lens. I have debated the results of such a combination, according to the known laws of optical instruments, with respect to magnification, illumination, visual field, etc. As the computation showed that in this way no essential advantages were to be secured, as compared with the simple concave lenses, it will here suffice to adduce those results very briefly. It is hereby presupposed that the first lens, so far as the mirror permits, is approximated to the observed eye, and that the observing eye lies close to the second lens.

First of all, as to the illumination; the maximum thereof is directly attained by a concave lens for the middle of the visual field. If the same thing is to occur by two convex lenses, then these must be so chosen and arranged that no other enlargement takes place than by the concave lens, that is, in such a way that the magnified retinal image of the flame appears to the observing eye under the same visual angle as the mirrored image of the flame does to the eye that is being observed.

If this enlargement is to occur, the image from the first lens must fall as in the ordinary ocular tubes of the compound microscope, in the middle between both lenses. In the case of a weaker magnification, it is possible to cause a larger portion of the visual field to appear in the maximum of brightness; in the case of stronger, on the contrary, that can no longer occur even in the middle. As advantageous, therefore, as even a stronger magnification might be, still such a one is not practicable, because the illumination would thereby suffer too much, and a living eye would not well endure for a longer time, without dazzling, the incidence of still stronger light than that reflected from a good lamp. Then, too, is the fact that the living eye cannot be thoroughly fastened, as would be necessary for the fixation of individual parts of the image in the case of stronger magnification.

Next to be considered is the visual field. The part of the retina which one can survey is always the smaller the farther one removes oneself from the observed eye; the larger the nearer one comes to it. The limit of approximation is, however, set in this way: that the obliquely placed mirror-plates have to be inserted between the eye and the glass-lenses.

In order to compare by means of computation the effects of various lenses we must therefore accept as equally great the distance of the concave glass and that of the first convex glass from the observed eye. If then at the same time the condition is observed, that the brightness in the middle of the visual field should reach its maximum, then are found definite focal distances of the convex lenses for every given distance from the eye which make the visual field at its largest. If one choose the focal distances of both the convex lenses in accordance with these determinations, then it further appears that when the distance of the lens from the eye is smaller than the focal distance which one may give to the objective of a telescope from the aperture of the pupil without prejudicing the distinctness of the image, therefore in the case of achromatic lenses smaller than perhaps the ten-fold pupillary diameter, the concave lens, if larger, the convex lenses can give a larger visual field.* Now, in the case of the closest possible approximation of the lenses to the observed eye, the distance between both will of course, on account of the mirror being placed in the interval between the lenses, remain in general somewhat larger than the tenfold pupillary diameter, and one would therefore be able to secure by means of two convex lenses a slight advantage for the visual field. Inasmuch, however, as the lenses, in order to yield this advantage, must have focal distances of 36 to 40 lines, it may become very difficult to receive an image of the same distinctness as by a concave lens which may have a focal distance of 8 to 10 inches. I, at least, have not been successful in this matter, by the combination of such convex lenses as stood at my disposal. Moreover, it transpired, in the experiments with such lenses, that the correct location of the instrument for the perception of the retinal image is both found and kept with much greater difficulty. With a simple concave lens it is, to wit, not necessary that the axis of the lens be directed exactly upon the observed eye, if only the mirror casts light into it. This condition, however, must be observed in the case of two convex lenses.

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* This sentence is obscure in the original and it does not seem proper to try and "read in" any conception of our own—[Ed.].

Consequently it appears to be more advantageous to retain the simple concave lens as ocular, while one almost everywhere else in optics replaces it to decided advantage by convex lenses. A decided advantage of the latter occurs, to be sure, even in our case, which would make their employment desirable, to wit; the advantage that, by an altered distance of the lenses from each other, one can adjust the apparatus to all visual distances of the observed and the observing eye, while, for this purpose, one must exchange the concave lens for another. If one could completely make stationary the head of the observed person and the instrument, convex lenses would in consequence be more convenient; without such arrangements, however, all their other advantages are outweighed by the disadvantage of the difficult placing of the instrument. I have therefore myself always employed only a simple concave lens.

3 Description of the Ophthalmoscope

In order to institute observations of the kind described, it is convenient to unite the mirror-plates and the concave lens by means of a suitable frame. I propose for such a combination the name *Augenspiegel*, by analogy with similar instruments. The instrument is viewed in Fig. 2 from in front, in Fig. 3. exhibited in horizontal cross-section. The reflecting plates *h h* are fastened, by means of the brass piece *g g*, to the circular plates *a a*, at an angle which is equal to the chosen angle of incidence of the light rays—in the figure, 56°. The brass piece *g g* forms with the glass plates a hollow, right-angularly triangular prism. In Fig. 3 one sees into the inner cavity thereof, and has before him one of the right-angularly triangular basal surfaces. Of the three quadrangular lateral surfaces of the prism, that which corresponds to the hypothenuse of the basal surface, is formed by the glass plates, that which corresponds to the longer cathetus stands free, that corresponding to the shorter cathetus lies in the disc *a a*, and carries a cylindrical process *p*, which, by means of a corresponding circular opening in the plate *a a*, so clasps through that it holds the prism fast against the plate, but permits a turning on its axis. The glass plates are held against the prismatic brass piece by the frames *k k k k*, whose over-reaching lateral edges are secured to the brass piece *g g* by the screws *l l*. The disc *a a* rests on the cylinder *b b c c* without being permanently fastened to it. In the border of *a a*, namely, there are cut four openings of the form *f*, to which openings there correspond four screws *e e* with cylindrical heads and thin necks, inserted into the border of the cylindrical ring *b b*. In Fig. 2 are shown only two of these screws, in order to let the holes *f* be seen. The heads of the screws allow of their showing through the broad circular portions of the openings, and if then the disc *a a* is turned about its center, the necks of the screws pass into the smaller, slit-shaped part of the same opening, while their heads lap over and fasten the disc to the ring *b b*. In that way it is possible to remove the disc very easily and quickly from the setting of the concave lens, and to exchange the lens for another. The concave lens *n n* lies between the plate *a a* and the floor of the cylindrical piece *d d*, which is screwed into *b b c c* and can be set back by screwing round, when it becomes necessary to lay two lenses one upon the other for very short-sighted eyes. The whole is fastened to the handle *m*. For a normal-eyed observer, the numbers 6 to 12 of the ordinary concave spectacle lenses, are sufficient for the adjustment to all adaptational conditions of the eyes to be investigated. For the viewing of other normal eyes, I generally employed Nr. 10. For very short-sighted eyes, two lenses should be superimposed.

As to the reflecting plates, those of ordinary mirror-glass are not appropriate, because their two surfaces are as a rule not sufficiently parallel to cause the images which they cast of the lamp-flame to coincide in the way that they should. The glasses must therefore for our use be especially ground, in order to receive parallel surfaces, though this condition need not be fulfilled with such exactness as in the case of the plane-parallel glasses which one employs in the finer measuring instruments.

A good blackening of the non-reflecting surfaces is essential. Since, of the bright light which falls upon the instrument, only a proportionately small part returns from the retina of the observed eye, all the remaining remnants of the light, which might perhaps get into the eye of the observer, must be done away with. First of all, the inner surface of the ocular piece *d d* must be blackened, and the observer must place his eye as closely into it as possible, in order to cut off all the light which could fall from the flame upon this surface. Secondly, the outer surface of the disc *a a* and of the prismatic mirror-frame *k k k k* must be blackened, in order that blank metal surfaces, which are turned toward the observed eye, may not produce disturbing corneal reflexes. Thirdly, however, the inner surface of the mirror-frame is to be blackened with especial care. The light of the flame which falls on the reflecting plate, passes in greater part through, and strikes the plate *g g*. All that is not here absorbed returns to the mirror, is reflected from this in the same direction to the observing eye, in which the weak light from the retina of the observed eye arrives, and mingles with the image of this membrane. I have found, in this matter, the general methods of procedure of mechanics for blackening brass pieces to be inadequate, and the framework of the mirror must be tapestried internally with black velvet, which absorbs the light more completely.*

When one desires to use the instrument, he sets the person to be examined in a dark room and next the corner of a table on which, at a level with the eye and sidewise from the face, stands a well burning, double draught lamp. It is convenient to set upon the table, at a fitting visual distance, some not too bright object, whereon one can point out to the observed eye certain points for fixation, for example a blackboard divided into squares, each of which is designated by a number, while one causes the eye to fix various points one after an-

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*The subsequent history of the ophthalmoscope "down to a time within the memory of men still living," is, very briefly, as follows: Ruete, in 1852, invented the "indirect method" (*D. Augenspiegel u. d. Optometer*, Göttingen, 1852). He employed a concave perforated mirror, held at a considerable distance from the observed eye, and between the mirror and the eye one (sometimes two) spherical convex lenses. Helmholtz, also, had made use of convex lenses, but these he had placed *behind* the mirror, finding them there, of course, of very little value (see herein).

Helmholtz, next, explained most thoroughly (*Vierordt's Archiv.*, 1852, p. 827) the method which Ruete had invented. In the very same paper Helmholtz described what he called "the simplest method," by which an eye could be examined by means of only a candle, a screen and a convex spherical lens. He also mentioned (still in the same most memorable article) the so-called Rekoss discs—*i. e.*, two rotary discs, each containing four concave lenses inserted not far from the peripheries of the discs. One of the discs held lenses from 6 in. to 9 in. focus, the other those from 10 to 13 in. The Rekoss disc, or discs, with numerous modifications, is, as all are aware, in use at the present day. Rekoss was not an ophthalmologist, but an instrument-maker of Königsberg (where Helmholtz at the time was living).

Coccius, in 1853, invented an instrument which found much favor for years. It consisted of a lens, set in a frame, in front of a plane mirror. The distance between the mirror and the lens could be altered very considerably.

Eduard Jaeger, in 1854, produced a combination of the Helmholtz and the Reute instrument—that is to say, the plates of silvered glass in the Helmholtz instrument were made replaceable by a concave silvered mirror, such mirror to be used for the indirect method. To this affair of Jaeger's, Strawbridge, of Philadelphia, in 1871, added three interchangeable Rekoss discs.

The opthalmoscope of Liebreich is too familiar to all to require the slightest description. So, almost, is that of Loring, with its single disc and double row of lenses, the disc being movable up and down for the purpose of bringing into action either the one row or the other. Wadsworth, of Boston, invented the "mirror obliquely set," which enables the observer today to look straight through the lenses instead of at an angle. Both the Loring and the Wadsworth instruments are especially valuable for refraction purposes.

The electric light ophthalmoscopes are in the hands of every practising ophthalmologist at the present day, and require no description.

ther. The image of the flame falls ever on different parts of the retina, which the observer, therefore, may investigate one after another in any order desired. Between the flame and the observed eye an opaque screen must be erected, in order to shade the eye, so that directly incident flame-light may not produce a very disturbing corneal reflex and a narrowing of the pupil. Still, the border of the shadow must pass very close before the observed eye, in order that the ophthalmoscope, which must itself remain in the light, may be carried toward that eye as closely as possible. The observer seats himself before the observed, brings the ophthalmoscope, without at first looking through it, into about the right position, when its reflecting surface casts a bright light upon the face. When one has so turned the mirror that the middle of its light falls upon the eye, and the axis of the instrument is directed precisely into it, one looks through. A person then has, as a rule, at once before him the bright image of the flame, or finds it after more or less moving about. Moreover, one can also, looking through the instrument, discern, to a certain extent, the eye and the clear light which must fall upon it, even if indistinctly and as if they were faded, and also, in that manner, with the help of these [the eye and the light upon it] discover the correct position. If, though the pupil appears luminous, one cannot see the various parts of the retina distinctly, then one must insert another concave lens. An observer who has accustomed himself to alter at will the adaptation of his eye easily discovers whether he sees more plainly by a far-sighted or a near-sighted adaptation, and whether, accordingly, he must choose more or less strongly curved lenses. Moreover, many persons make the matter difficult, especially those who are not accustomed to looking through optical instruments, and short-sighted persons who see through them with difficulty, insomuch as they involuntarily adapt the eye for great nearness, because they think of the object to be seen as being very close. In that way the eyes of the observer are greatly fatigued, and readily begin to be injected and to water. It is necessary here, as in the case of all optical instruments possessing an alterable adaptation, to adjust the eye for the distance, and then to adjust the instrument to the eye.

After a little practice it is not difficult to find the right lens and the correct position of the instrument. Also, one can easily, on his own eye, show these matters to anyone who has never yet seen them, in order first to render him familiar with the appearance of what he is going to look for. In that way it will be made much easier for him to discover independently the very same things in the eyes of others. Let the instructor, for this purpose, first of all discover the particular lens through which he can see the student's retina plainly, and then let him place this in the ophthalmoscope; then through the same glass the student can see distinctly into the eye of the teacher, if neither of the two is very short-sighted. In the latter case (as explained already) the more short-sighted person needs a somewhat weaker glass when he observes than when he is observed. Let the instructor, then, bring one of his own eyes into the position which has been described as that for the eye to be observed, and let him so hold the ophthalmoscope before him that he may be able, at the same time to look, through its central openings and glimpse the mirrored image of the flame in the mirror, hand over to the student the instrument in this position, and let him look through it. The student will then see in the eye the image of the flame. In order to teach him to recognize the appearance of the parts of the retina, let the teacher throw the image of the flame on the place of entrance of the optic nerve, because in that place the largest and most recognizable vascular trunks exhibit themselves. Let him, for this purpose, turn the eye gradually more and more to the inner side of the mirrored image of the flame, until this suddenly becomes smaller to him, or disappears. That happens, as is known, when the image falls upon the place of entrance of the optic nerve. Besides, most persons more easily succeed in seeing and recognizing the image of the flame than the tiny parts of the retina in the bright ground thereof.

4 Viewing the Retina and the Image of the Flame

Should one desire to investigate the retina completely, then it is convenient, as already mentioned, to set up a blackboard covered with numbers as a visual point for the eye to be investigated. As soon as this eye fixes one of the numbers, looking past the mirror a little to the inward side thereof, the observer will almost always recognize in the visual field one or two of the larger vessels. He causes the eye to turn to one of the near-lying figures, and notices whether he is brought nearer to the origin or to the branching of the vessels. While, in this way, he traces the vessels in the direction of their larger trunks, he comes at length to the place of entrance of the optic nerve. This distinguishes itself from the rest of the eye-ground by its white color, for it is not covered with pigment and a fine vascular network, but here the white cross-section of the nerve lies wholly free, at the very most shot through by tiny, isolated vessels. Mostly to the inner side, near by, the arteries and veins of the retina press forward from the depths. At times one sees a portion of the vessel still hiding in the substance of the nerve, and understands that, in the living, this substance is decidedly transparent. One distinguishes the two kinds of vessels from each other by the brighter color of the blood and the double contours of the walls in the arteries and in their first ramifications. I have not been able to recognize pulsations with certainty. The first main branches of the vessels border the optic nerve at its inner side, in order to spread out later, above and below, across the retinal field. The appearance of the sharply pencilled red vessels on the clear white ground is of surprising elegance. Somewhat farther to the inner side, close by the nerve, I have always remarked a small, sickle-shaped stripe of shadow, which appears to take its origin from a fold of the retina.

In the other parts, the ground of the eye looks reddish, and indeed first of all round about the optic nerve, of a somewhat clear, light-red, the darker, on the contrary, the farther you pass from that place. One sees here larger and smaller branching blood-red vessels, which stand out plainly from the background. The ground itself appears to be not entirely homogeneous, but indistinctly reddish. This would seem to arise from the fact that the close capillary net is too fine, too weakly illuminated and too transparent to be distinguished plainly from the underlying weakly, light-gray substance of the retina. That the ground looks brighter in the vicinity of the optic nerve is no doubt owing to the fact that the retina here, on account of the superimposed fibres of the optic nerve, is thicker, while, toward its periphery, it becomes continually thinner. Moreover, the place of direct vision (the yellow spot) is essentially distinguished in appearance from the parts which lie immediately about it. In order to get this point before oneself, one causes the eye which is being observed to look directly at the mirrored image of the flame. The retina then appears much darker, grayish-yellow without intermixture of red; and one sees no traces of capillary vessels. Then, too, one is greatly annoyed while gazing on the yellow spot, by the tiny image from the cornea, which obtrudes itself precisely in the center of the visual field, while, during the observation of the lateral portions of the retina, it lies to one side.

After deciding what, in the healthy eye, can be made out concerning the nature of the retina, I have no doubt that one will be able to recognize all such disease conditions as permit of recognition by the sense of sight in other transparent parts —for example, the cornea. Increased repletion of the vessels and vascular varicosities must prove easy to make out. Exudates into the substance of the retina, or between that structure and the pigment membrane, must yield themselves to observation, very much as affections of the cornea do, by their brightness against a dark ground. If they lie in part before the retina, they will then enclose its vessels in a veil. I here recall that, according to Brücke, the recent retina is just about as transparent as the other ocular media, and that apart from its vessels, it is only visible in our experiments because it is strongly illuminated on the deep-black ground of the pigment membrane. Fibrinous exudates, which are nearly always less transparent than the ocular media, must also for that reason, when they lie in the fundus of the eye, considerably strengthen the reflex. Then, too, I believe that opacities of the vitreous body will be much more easily and certainly recognizable, partly by the illumination of a reflecting glass-plate, partly by the ophthalmoscope. One will even be able to determine with ease, from the indistinctness of the image of the flame and of the retinal vessels, the degree of the opacity. If, in the case of such an opacity, scintillating particles have detached themselves, then too a person will be able to take note of these. In brief, I believe that I may hold the expectation not to be exaggerated, that all the alterations of the vitreous body and of the retina which, until now, have been found in cadavers, will also permit of recognition in the living eye—a possibility which appears to promise the most remarkable advances for the hitherto undeveloped pathology of this structure.*

Finally, it is of interest, for certain physiological purposes, to investigate the accuracy with which the eye forms images. It is best to employ for this purpose a thread, which one draws along horizontally before the flame. Its image remains single, while vertical threads are manifolded by the manifold reflections.

First of all one gets an opportunity to convince oneself, by the appearance of the image, that the different adaptations of the eye really depend upon alterations in the refractive media. One should cause to be fixed an object which is just about as far removed from the observed eye as the thread is from the flame. The observer then sees the elements of the retina and the image of the thread distinctly at the same time. Should the thread be carried nearer to or farther from the eye, then it becomes indistinct in the retinal image, or entirely disappears, while the parts of the retina remain sharp. One perceives from this that the retinal images of objects which stand at various distances from the eye, are in fact not equally distinct. Then again, one should so place the thread that it appears distinct in the retinal image at the same time with the vessels, and should cause the observed eye to fix a point which is either much farther or much nearer than that upon which it was formerly directed. Immediately one sees the retina and the image of the flame become gradually indistinct.

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* Probably the most significant sentence ever penned by an ophthalmologist. How gloriously the great man's prophecy has been fulfilled is known not merely to specialists and general practitioners, but even, in some degree, to first year medical students and the educated portion of the laity. In fact, there are just two kinds of ophthalmology, that which came before and that which followed after Helmholtz's "*Beschreibung eines Augenspiegels.*"—(T. H. S.)

It should incidentally be remarked that, on the white surface of the optic nerve no image is cast, even when the image appears absolutely sharp on the immediately surrounding portions of the retina. Inasmuch as the observer, in the case of a person over whose optic nerve cross-section little vessels run, sees these quite as plainly as those of the retina adjacent, therefore that indistinctness of the image of the flame cannot proceed from the passage of the end of the optic nerve out of the level of the retina. I believe rather that one must regard the transparent condition of the optic nerve mass as the real cause.

Moreover, one is able, whenever it becomes necessary, to convince oneself readily in an objective manner of the presence and the degree of the short- or far-sightedness of the observed eye. Let the observer first investigate a normal eye, which he causes to fix objects at various distances, and notice what concave lenses he is obliged to use in the various stages of adaptation of the eye. In the investigation of any other eye, he then learns from the number of the concave glass through which he saw the retina distinctly the corresponding adaptational distance of the observed eye. The observer is, by this method, entirely independent of the assertions of the other person, for he himself sees, as it were with that other's eye, at least by means of its refractive media. In this way, for example, I was able to convince myself in a completely amaurotic eye, that that eye was simultaneously in a high degree short-sighted. In that way was decided in this case a question of great importance for the anamnesis, whether, that is, certain earlier difficulites of sight recounted by the patient should be referred to short-sightedness or to commencing amblyopia.

An important physiological conclusion thrust itself upon me in these investigations. The free-lying cross-section of the optic nerve is apparently so transparent that the light which falls upon it must penetrate deeply into the mass of the fibres, inasmuch as, now and then, one sees the bendings of the central artery and vein shimmering forward through the substance of the nerve. When the little image of the flame falls on the place of entrance of the nerve, then all its fibres, or at least a very large part of them, are struck by more or less intense light, and yet, obviously, they perceive no light. If they did perceive it, then that entire portion of the visual field which corresponds to them would have to appear illuminated. Not only, however, is that not the case, but there is even less light perceived than when the image falls upon some other portion of the retina. We must from this conclude that the fibres of the optic nerve are incapable of being affected by objective light (ethereal vibrations), while, nevertheless, they perceive every other kind of irritation as subjective light. This is a paradox which, of course, has its ground in the ambiguity of the word "light," and is far removed from being an actual contradiction. The vibrations of the ether which we call light, produce, like every other mechanical or electrical irritation, when they strike the retina, the sensation which we call light. But from this, that the retina, protected from pressure and electrical currents and exposed to the action of ethereal vibrations, is much oftener struck and excited by the former than by the latter, it by no means follows that light must be regarded as an especially adequate irritant for the retina and the elements of the optic nerve and as standing in contrast to all the other kinds of irritation. There are no difficulties in supposing that all the irritations which are able to affect the optic nerve system produce sensations of light, that, however, the ethereal vibrations are able to act only on the retina. A similar state of affairs is found in the case of the nerves of touch, with respect to heat and cold. Here too the peripheral expansions behave differently from the trunks. For the latter, slight variations in temperature are no irritant at all, as it appears, and the greater variations, which are able to irritate, produce no temperatural sensations. Besides, one is able to conclude still further that, in the retina, not the fibres, which spread out in a radiating manner from the optic nerve, but the spherical elements, are sensitive to light. Were it the former, then must light which strikes on any place in the retina be perceived by all those fibers which in part end in this place, and in part pass across it on their way toward the retinal periphery. There would therefore extend, in the visual field, from every illuminated point, a bright shine toward the borders of the field, which is not the case. We may accordingly further conclude that even the continuations of the optic nerve fibres in the retina are insensitive to light. There remain only the ganglionic bodies and the nuclear-like structures of the retina, in which the ethereal oscillations are able to act as an irritant.

Appendix

Derivation of the formula for the quantity of light which is reflected from several glass plates.

Whether this formula is correct for n reflecting surfaces is shown by the fact that it is also correct for $(n + 1)$. As it also proves right for $n=1$ and $n=2$, it must do the same for any desired value of n.

Let the quantity of light which at the given angle of incidence is thrown back by a reflecting surface, when the quantity 1 passes off of light polarized vertically against the plane of incidence, be p, that thrown back by n such surfaces $P_{(n)}$, that thrown back by $(n+1)$, $P_{(n+1)}$. It is demonstrable that if

$$P_{(n)}=\frac{np}{1+(n-1p)}\ldots\ldots\ldots\ldots 1)$$

then also that equation is correct which arises from this by the substitution of $n+1$ for n:

$$P_{(n+1)}=\frac{(n+1)p}{1+np}\ldots\ldots\ldots\ldots 2)$$

For the sake of a better designation, let us assume that the system of *n* reflecting plates lies horizontal and that light falls on it from above. Let the $(n+1)$th surface be added to the system below. The quantity of light which passes downward from the lowermost nth surface of the compound system to the $(n+1)$th surface let us call x; that which reflected from the $(n+1)$th surface, mounts to the system of the n surfaces, y. The quantity x is composed partly of the portion of the incident light which has passed through the system of n surfaces, partly of the portion of y which is reflected from this system. Therefore is

$$x=1-P_{(n)}+yP_{(n)}\ldots\ldots\ldots\ldots 3)$$

The quantity y originates from that part of x which is reflected from the $(n+1)$th surface. It is therefore

$$y=xp\ldots\ldots\ldots\ldots 4)$$

The quantity $P_{(n+1)}$ which passes upward from the uppermost surface, proceeds in part from that portion of the incident light which is reflected from the system of n surfaces, partly from that portion of y which passes through this system. It is therefore

$$P_{(n+1)} = P(_n) + y\,[1 - P(_n)] \ldots\ldots\ldots\ldots 5)$$

If one eliminates x and y from equations 3, 4, and 5, one gets

$$P_{(n+1)} = P(_n) + \frac{p[1 - P(_n)]^2}{1 - pP(_n)} \ldots\ldots\ldots\ldots 6)$$

If we place in this equation 6 the value of $P(_n)$ from equation 1, we get in fact, after the necessary reductions, equation 2, whose correctness was to be proved.

For *one* reflecting surface is

$$P(_1) = p$$

Equation one (to be tested) gives the same value.

For *two* reflecting surfaces we get the value $P(_2)$ without employing equations 1 or 2, if, in the derivation of equation 6, we suppose that $n = 1$ and $P(_n) = p$. Equation 6 then becomes

$$P(_2) = p + \frac{p\,(1 - p)^2}{1 - p^2}$$

$$= \frac{2p}{1 + p}$$

Equation 1 gives the same value.

As the latter accordingly is correct for $n = 1$ and for $n = 2$, then it follows from the proof adduced, that it is correct also for $n = 3$, and if it is correct for $n = 3$, that it also is correct for $n = 4$, and so on to infinity.

In a precisely similar way the matter proceeds in the case of light polarized parallel to the surface of incidence.

If we assume the quantity of incident light to be equal to $\frac{1}{2}J$, and that $p = 2P/J$ and designate that which we have here called P with Π, we get the formula in question.

Superior,
Wisconsin.

Editorials

The Centenary of the Birthday of von Helmholtz

ONE hundred years ago this coming August there was born into the home of simple but most excellent parents a boy destined to mature to manhood and to become one of the world's greatest scientists and one of her first citizens.

Indeed it is meet and proper that the birthdays of great men and women should be celebrated. For the great things of the world are accomplished by men and women of great capacities who, in departing "leave behind them footprints on the sands of time" which serve as guides to those who come after them and as ever-present sources of inspiration.

Every nation commemorates the birthdays of its national characters—the men and women who have served for the common good and the betterment of mankind. Some of these have been great in war and others have been "first in the hearts of their countrymen"; some have been captains of industry, while others have thought not of the loom and the ploughshare but have labored that man might have the treasure which neither moth nor rust doth corrupt. Such men and women have been acclaimed in large measure first of all by their own peoples, to be later venerated as Citizens of the World.

The scientist is a member of a state but belongs to no state. At heart he is a man of peaceful purposes and pursuits, being desirous of contributing to the immense volume of science some fragments which may prove good and which may become a part of the ultimate, sum total of all knowledge, to the end that man may become master of the unseen forces about him. Scientific men and women and those who are possessed of that spirit have no regard for color, race or outer appearance; they are Citizens of the World. Therefore, with great propriety, it is not a galaxy of national names which claims their attention and catches their minds' eye, but rather the keen judgment of the worth and value of a laborer in the vineyard of science through his works and his influence upon other workers. As men and women interested in science, we ought to appropriately commemorate the birthdays of some of the humble yet great workers in the vineyard of science.

A little note accompanying the sketch of the life of von Helmholtz and personal reminiscences by Dr. Mendenhall called our attention to the fact that the centenary of the natal day of this great genius, von Helmholtz—and doubtless "the world will never see another" such an one—occurs this year. We should celebrate his birthday by communing with him through the medium of the records of his marvelous intellect preserved to us in the printed page. Much of that which he accomplished is not available to many of us by virtue of the fact that there is as yet no world language in which the substance may be communicated without the embarrassment of the difficulties of the means of conveyance. And so, since we have believed that all interested in any wise in the human eye would wish to celebrate this anniversary day by sitting in conversation at the feet of this great master, we are presenting the original essay on "The Description of an Ophthalmoscope" as translated by Dr. Thomas Shastid.

We know of no better way to close this message or to further supplement the delightful sketch written by Professor Mendenhall than to quote from the reminiscences of von Helmholtz as taken from an address by our own Dr. Casey A. Wood, as he writes:—

"Helmholtz stood for sobriety and simplicity in living. He was a quiet but effective example of the democracy in science, and, although the most social and kindly of men, he had no time for the ordinary distractions of society. It is true that conditions in his own country rather emphasized this Spartan attitude; it is always easier to make a national virtue out of a national necessity, but, after all, the temperamental virtues and the simple life go not unnaturally together.

"I think I have elsewhere related my experience of the style observed by the various teachers in the *Physiologisches Institut* at Berlin when I was first a student in that school of learning more than a quarter of a century ago. Every now and then one of the teachers would invite his colleagues and some of the students to a modest repast—generally known as a *Microscopische-Bier-Versammlung*—at which we talked, ate sandwiches and then talked some more, not only about the special matter in hand, but about everything else under the sun. The simple, almost primitive character of the material entertainment, contrasted with the elaborate and priceless quality of the spiritual and mental food, made an enduring impression on my mind. Looking back on those happy, carefree days, I believe at the time it was more the unobtrusive informality of these meetings,—if I must use the word, the frugality of it all,—that I remember most decidedly. Truly the greatest are often the simplest of men. Just think of it: we listened in their hours of ease, to the conversation of Helmholtz, Du Bois Reymond, König, Fritsch, Gad, and a dozen others at that time less widely known, but since become famous.

"I wonder what importance you as citizens of a free state attach to the waste of life, of money and of energy that goes on all about us, and, for the matter of that, in the bosom of our own families. None of us wishes to be regarded as a croaker or even to rank as a Jeremiah, but what in the name of Hygeia, or any other goddess, is the meaning of it all? Is it a passing phase in the development of a new world, to be corrected by time and experience, or are we going to seed prematurely, to be finally purified into the Gehenna of nations? Personally, I do not 'despair of the Republic', but I cannot help thinking that it is foolish to mistake mere display for effectiveness, to accept lavish expenditure in lieu of high thinking, to substitute the shadow for the reality. Of course, the difficulty generally is, how, in the face of serious obstacles, to live our own lives properly, yet how can *we* consistently and effectively criticize that deplorable waste and extravagance in public and private life that we, better than anyone else, know to be abundant everywhere, unless we demonstrate the faith that is in us by simple and hygienic habits?

"I am sure that Helmholtz was not a mere ascetic. Although a tireless worker and a deep student, he liked the good things of this world, but he fervently desired, first of all, to bring them within the grasp of others; and he believed that it is mainly through the appreciation of scientific discovery, advanced education, and rational living that the general level of mankind would be raised to higher things, that more solid satisfaction is to be derived from a dollar rationally spent in the public service than from ten cast into the ditch of selfish enjoyment. But to attain this Nirvana the individual must begin early, the nation must begin early, must keep it up and keep always at it. The price of personal and national advancement is that of liberty—everlasting vigilance.

"We have heard a good deal about the story of the simple life in recent years, and we know that it is only the revival of that gospel preached by philosophers when Babylon and Thebes were young, and long centuries before Rome was founded or Paris dreamed of, but I attach some importance to the knowledge that Helmholtz thought it worth while to champion it, and that he did what he could to foster plain living in conjunction with exalted thought.

"During his long and eventful career Helmholtz, in pursuance of the belief that the salvation of the race lies chiefly in the rational application of painfully acquired knowledge, found time to give popular lectures to those he thought would appreciate them. These lectures were prepared with great care and were fully illustrated, often by experiments. The text of these lectures, both in the original and in their translation, is a model of literary style, while the subject-matter is inspiring and instructive. I have long felt that we have been very derelict in our duties as teachers and as guides of public opinion.

"Finally, gentlemen, I would like to speak of a characteristic of Helmholtz that, developed more or less in many great men, is sufficiently uncommon to be worthy of comment. Perhaps, also I think of it because I once played a minor part in the exhibition of this quality of the master. I refer to his scrupulous and kindly regard for the failings, claims, and rights of others. You will recollect that although Helmholtz was undoubtedly the first to give an intelligent and complete explanation of the mechanism of accommodation, he declared when the papers of Cramer were laid before him some time after the publication of his own researches, that the Dutch observer and not Helmholtz should have the honor of the discovery, that he had done little subsequent to Cramer's solution of the main problem to elucidate the theory. Again, Helmholtz's discussion of the claims of those who had *almost* invented the ophthalmoscope, as well as his attitude toward those who subsequently improved upon the first model, are couched in the same terms of praise of their efforts, with but few remarks about his own.

"Indeed, he seems to me to have exemplified Bayard Taylor's dictum that

'Fame is what you have taken,
  Character's what you give;
When to this truth you waken,
  Then you begin to live.' "

The Movements of the Eyes During Reading

MOST persons have quite erroneous notions as to what their eyes do while engaged in the act of reading. Ordinarily we are quite unconscious of the movements of our eyes except when these movements are rather wide or when we indirectly infer their existence from the change in the objects seen. We know that we cannot read an ordinary line of print without moving our eyes in some manner along the lines, but introspection gives us little information concerning the nature of the movements

Apparently no one prior to 1879 ever mentioned the fact that eye movement, as in the act of reading, is not continuous but rather discontinuous. It was the great French savant, Professor Javal of the University of Paris, who called attention to this fact. Javal, in company with Lamare, conducted by simple methods a number of studies of eye movements from which it was concluded that the eye moved over the line in a series of jerks interrupted by pauses and that no reading was done except during the pauses. By attaching a microphone to the eyelids he could hear the faint rustling sound made by the cornea against the lids and he estimated that the pauses came about once every ten letters. He also believed, from experiments made in reading lines cut in halves horizontally, that the upper part of the line was more important than the lower part, and that the point at which the reader's gaze was directed, *i.e.* the fixation point, was slightly above the middle of the horizontal line of letters and that it did not waver above or below the line itself. Most of these inferences have not been substantiated by later experiments.

In 1891 Landolt published results obtained by watching the movements of the eye in a mirror. His experiments showed that in reading a foreign language, numbers, lists of proper names or disconnected words in general, more fixations were needed. He concluded that 1.5 words, on the average, were read at each fixation.

Several attempts were made by various experimenters to attach recording apparatus directly to the cornea of the eye. Finally, in 1898, Professor Delabarre, of Brown University, succeeded in improving this method and secured tracings of ocular movements, though not of the movements during reading.

These ideas were carried further by Huey who, working at Clark University, attached a very light plaster of paris cup directly to the cornea and recorded the eye movements by a system of light beams which were so arranged in conjunction with suitable electrical devices as to provide a measurement in very small fractions of a second of the time used up by an eye in the movements of reading. The results obtained by Huey and which are of interest to us include:—(1) In reading relatively long lines of magazines, the average number of fixations is about 4.5 per line: (2) Doubling the distance from the eye to the page does not affect the number of fixations: (3) Minor modifications in the size of the type do not affect the number of fixations: (4) The duration of the reading pauses, though extremely variable, averages about 0.19 second: (5) Fast reading entails fewer and shorter stops or pauses, but not faster movements: (6) A short line, *e.g.*, about 60 mm., makes possible fewer pauses, relatively, so that more is read with the single pause: (7) The movements forward, *i.e.*, from left to right, are quite constant at 0.042 to 0.048 second: (8) The movements of return, *i.e.* from the right end of a line to the left end of the next line, are quite constant at 0.051 to 0.058 second. It has been found by later work that these last two generalizations are incorrect, since these time periods are too long.

Erdmann and Dodge in 1908 published the results of experiments performed at the University of Halle. Their conclusions are: (1) The number of pauses for reading is fairly constant for the same reader using the same material, but is affected decidedly by length of line, by difficulty of material read and by the personal equation of the reader: (2) The first fixation is not at the extreme left end of the line, but a short distance from this end, while the last fixation, similarly, is often not at the extreme right end but at a short distance from that end: (3) The fixations seem to be on words and usually on the middle of a word (a conclusion which does not seem, in some respects, to have been borne out by later experimentation): (4) Of the entire time spent in reading from 12/13 to 23/24 is devoted to the pauses, the remainder to the eye movements: (5) It is extremely doubtful if anything is perceived during the movement.

From 1900 on, Professor Dodge developed at Wesleyan University a new and vastly superior method of reading, recording and measuring eye movements in reading. In this device, the cornea of the eye was illuminated by an actinically powerful beam of light and the moving cornea was photographed through a narrow slit upon a very sensitive plate arranged to fall vertically at a constant and controllable speed. No inconvenience is experienced by the reader, but the precision is such as to enable the exact location of the fixation to be subsequently located upon the printed page to within an error of one small letter. He showed that the speed of the forward movements averaged about twenty-five thousandths of a second, while the speed of the return movements was of the order of forty thousandths of a second.

W. F. Dearborn employed Dodge's photographic method in work carried out at Columbia University, and in 1906 published the latest information which we have at hand on the work done by the eye muscles in the process of reading and from it the following summary of results may be obtained, as pointed out by Professor Whipple of Cornell University.

1 The speed of forward movements determined by Dodge is confirmed: they are then nearly twice as fast as Huey reported, and it follows that no reading is done, or could be done, during these movements.

2 The duration of the fixation pauses is, roughly speaking, around one-fifth second: thus, in reading a newspaper column, four readers averaged 161, 216, 255 and 402 thousandths of a second, respectively. The duration is therefore different with different readers and is found to play an im-

portant part in conditioning their speed of reading. When the same reader is able to reduce the number of pauses, the duration of each pause tends to increase, but relatively there is a saving of time.

3 For a line 96.5 mm. long, there were on the average of 7.45 fixations, so that 1.6 words were read per fixation.

4 Fixation is not absolute and constant, but only approximate; in other words, the eye often makes slow gradual changes of position during a fixation.

5 Likewise, fixation is not extremely precise with regard to the position vertically along the line; it is not as Javal thought, confined to a straight line between the middle and top of the small letters, but wavers slightly up and down, and these inaccuracies increase, seemingly, when the line is long, the type small or the leading too narrow.

6 Again, the forward jerks may be interrupted by backward movements, regressive movements, or fixations. These retracements are most common at the beginning of a line and in the first few lines of a passage, so that they indicate a preliminary difficulty in locating the left-hand margin, which is later on overcome as the eye gets habituated to the mechanical arrangement of the printing before it. It follows that the practise of breaking up the left-hand margin of the printing, as is so frequently done in primers and readers, is injurious, because it presents an unnecessary obstacle to the work of the eye. There are also occasional movements of re-fixation which seem to be due to the eye having run forward too rapidly for the assimilation of meaning.

7 The first and last fixations do generally fall within the edges of the printed page, but this varies somewhat with the reader and with the particular character of the words lying at either end of the line.

8 Fixation is not, as previously supposed, in the middle of words, but may be in practically any place within a word, or in spacing between words, nor does it fall more frequently in the first part than in the last part of a sentence. The

precise spot at which the gaze is directed is, then, indifferent as it is merely the middle of an area of clear vision.

9 It is possible, however, to show certain factors that determine the fixating of a given area. Thus, short connective and non-substantive words, prepositional phrases and relative clauses make the greatest demand on apperception, so that lines having many such phrases or words demand a large number of pauses. This is because these terms are not regularly associated into larger phrase units and must be separately attended to, unless the context makes the reader prepared or expectant for a particular collocation. Again, for some readers, the typography of the line may condition the precise location of fixation: capitals, dashes, punctuation marks, the so-called "dominating" letters—all tend to "hold up" the eye.

10 Fixation pauses are more frequent than is needed for clear seeing of the stretches read, as is shown by the fact that they remain the same in number when the print is removed to a double distance from the eye. Moreover, the work of Dockeray (1900) has shown that the span of clear vision with 10 point type at 35 cm. distance is 20 to 22 mm. on either side of the fixation point, or a matter of an inch and a half in all, a distance much longer than the forward eye movement.

11 As might be expected from the above statement, it is possible to be at least vaguely conscious, while reading one line, of the material lying in the succeeding lines.

12 There appears to be a tendency for eye movements to fall into rhythms, as shown for instance by the reading of six successive lines with four fixations each. Dearborn lays much stress on this point and believes that "these short lived motor habits" are formed more easily by fast readers, more readily when the lines are short and when their length is uniform and the margins are not too broken. When these rhythmic movements appear, they usually involve also a special manner of distributing time to the pauses, viz: a com-

paratively long initial pause, followed by two or more short ones of decreasing length and concluded by a somewhat longer pause near the right end of the line.

13 Dearborn recorded the eye movements of three children about ten years of age and declared that the chief difficulties of eye movement seem to have been conquered at that age. However, others claim that children make many more and longer fixations than adults, accompanied by decided uncertainty of movement—re-fixations, over-shooting of the line and the like.

14 The ultimate decision as to the optimum length of line depends on numerous factors of which eye movement is but one. When the line is shortened, pauses seem to be decreased in duration even though they sometimes increase in frequency. Again, short lines develop or favor the development of habits of rhythmic eye movement. Once more, the material seen vaguely in lines below that read is more closely connected with the material in attention when the lines are short than when they are long. Huey favors a line of about 60 mm. length and Dearborn, a line of 75 to 85 mm., or about one-third longer than the ordinary newspaper line. In this matter most primers and readers are again "grievous sinners", for their lines are often longer than those of ordinary books, often reaching 120 mm. or more.

15 Fatigue causes a slower rate of reading and a gradual decrease in the velocity of eye movements.

16 Problems of speed may be approached by comparing the performances of fast and slow readers. Tests show that an individual who reads a given style of material rapidly will read any material at a relatively rapid rate, so that more speed is rather a function of the personal equation than of the kind of material read. Actual differences are, however, even in persons of like occupation, rather extreme; thus, of thirty persons all interested in university work the slowest read 3.4 and the fastest, 11.5 words per second in Robinson Crusoe. Fast readers evidently drop more readily into rhythmic eye movement and make fewer and shorter stops.

Some Factors Affecting Visual Acuity

Charles Sheard, Ph.D.

VISUAL acuity is measured quite commonly in practice by the use of Snellen type. The letters on this chart are so constructed as to subtend an angle of five minutes when viewed at the distance for which they have been calculated and for which they are marked. The lines which form the limbs of the letters and the intervals which separate various portions of a letter (such as the letter E) are seen under a one minute angle. Within recent times a few charts have been made in which a four minute angle is taken as the standard. Tests made by Hooke and other astronomers and experiments by Mayer, Volkmann, Weber, Helmholtz and Bergmann upon the visual acuity minimum have indicated answers varying from 45 to 95 seconds. Therefore, the Snellen test-types of our clinics and offices are but assumed standards which are found to serve us rather conveniently in the practical work of ocular refraction. Hence, although it may be supposed that a normal eye has a visual acuity, $V = 1$, as a minimum on the standard adopted, this statement evidently holds for the condition of the majority of eyes which are normal in their ability to see. For the acuity depends not only upon the quality of the dioptric apparatus but also upon that of the retina, of the optic nerve and of the brain. Hence, certain differences may be expected to arise. In youth it is frequently better than unity: $V = 9/6$ to 12/6 is not uncommon and a case has been reported in which $V = 42/6.5$ or six and one-half times the normal. It is, therefore, to be said that various anatomical and physiological conditions may operate to either increase or decrease the acuity of an eye as compared with the visual acuity standard of the average eye.

Readability of Letters

It is a well-known fact that some letters are much more easily read than others on the same test line. The readability of a letter is, indeed, a very complex affair and does not appear to depend altogether on the size of the intervals separating the different lines of the letters. Various attempts have been made to remedy this by constructing the test-letters less readily seen on a slightly larger scale. Likewise, the manner and degree of illumination of a chart are questions of importance; at the present time various cabinet devices, with electric lamp and reflectors within, ensure a fairly uniform and sufficiently high illumination. And, again, the background and surroundings of the black test letters should be as perfectly white as possible; the writer is convinced from his experiments along this line that the readability and hence the visual acuity is considerably affected by a cabinet frame of black as compared with one of white set upon a white wall. There has been recently pointed out the desirability of having a single small light source in a large uniform background in muscle testing: it seems, therefore, desirable that there should be some device invented whereby all these various tests may be made with the objects under inspection, and which serve as a basis of various tests, rid of irradiation, color effects or the presence of other objects in the field of view. True it is that these and similar conditions exist in our everyday life and that acuity is markedly influenced by surroundings, but we need sets of conditions which are uniform in construction and operation in our work so that acuities in "California may check with those in Maine."

In the second report of the committee on Standardizing Test Cards for Visual Acuity of the section on Ophthalmology of the American Medical Association, of which committee Dr. Edward Jackson was chairman, we are told that three members of the committee made comparative tests on different individuals, noting the distance at which each letter was visible in the same light: the other two members compared the visibility of the letters at a fixed distance. The results of all methods and tests showed that B was the hardest letter to see and L the easiest. The letter B has been known for some time to be the letter which most nearly conforms to the standard five minute angle requirement of the Snellen test. Taking, then, the ability to recognize B at the five minute angle as standard vision, or V = 1, and comparing other letters with B, the average visual acuity required for the recognition of each is as follows:

L	0.71	D	0.82
T	0.74	Z	0.84
V	0.78	N	0.85
U	0.79	E	0.85
C	0.79	R	0.88
O	0.80	S	0.89
Y	0.81	G	0.92
P	0.81	H	0.92
F	0.81	B	1.00

The foregoing list necessarily gives only the order of the various letters as the averages of the different persons tested. It is perfectly obvious that two persons with full visual acuity and fully corrected ametropia will differ in the order of the visibility of these letters. "Apparently there is an individual difference in distribution of retinal elements, or in the connections and sensibilities of cerebral elements which prevents rigid exactness in the measurement of form vision". This is, therefore, an important reason for putting on test cards a fairly wide variety of letter forms.

"The positive suggestions for the use of these letters on test cards," says the report of the Committee of 1916, are as follows: The eighteen letters may be divided into four groups:

L T V U C
O Y F P D
Z N E R
S G H B

"Each group successively contains letters more difficult to recognize. Each line of the test card should contain at least one letter from each group; and the lines of smaller letters (the more used and more important lines of the card) should contain two letters from each group."

The most readily visible letters have a visual acuity value of about three-fourths as great as that of the letters most difficult to see. If the interval between successive lines be not greater than this a continuous series is obtained, the easiest letter on one line being an appropriate test, when the hardest letter on the line preceding it has been recognized. When, however, the interval between successive lines represents a change of 20 per cent in the visual acuity, the letters may be so chosen that reading half of an additional line will indicate a gain of one-tenth in vision, and the reading of the whole line two-tenths. A sample of a test-card arranged to embody these suggestions is as follows:—

Five Minute Distance, Meters	Letters used	Vision if Half are read	Vision if All are read
50	B	...	0.10
25	U H	...	0.2
16.67	T Z S	...	0.3
12.5	L Y N B	...	0.4
10	V D Z R G	...	0.5
8.33	C F N E S H	...	0.6
6.25	T U Y O R Z G S	0.7	0.8
5	V C D F E N S B	0.9	1
4.17	L U O Y Z E S G	1.1	1.2
3.57	U T D P Z R B H	1.3	1.4
3.12	T L Y P N E H S	1.5	1.6

In view of the fact that letters of the alphabet differ so much in the distances at which they can be normally seen, Landolt devised the split-ring test as a method for the expression of the degrees of acuteness of vision which can be used in all languages. The following are the six general principles laid down by the Congress of 1909 relative to the principles underlying the expression of the visual acuity:—(1) The test is based upon the "minimum separable" or the capacity to perceive an interruption; (2) the test is to be made by means of a black ring on a white ground, the ring to be broken at one place for a space equal to the width of the limb of the ring, which is one-fifth of its diameter; (3) the visual acuteness is to be expressed in relation to the smallest angle under which this can be deciphered, that is, to the maximum distance at which this can be done; (4) the visual angle of one minute is to be the standard of comparison; (5) the mode of expression is to be either in decimals or as a fraction ($V = d/D$), and (6) the eye is to be tested only at a distance from the test object.

Various forms of type or arbitary symbols all suffer from several defects; chief amongst these are that the transition from one size to another is not gradual and that the element of recognition enters in to assist the eye with certain details and not with others of the same size. Such defects are not overcome by variations of illumination or changes in the distance of the object. Presumably, therefore, an excellent test-object is one in which the size of the detail is the only variable. A simple apparatus has been devised by Ives in which it is claimed that this ideal is obtained in actual practice. The test object consists of a pair of oblique line gratings which can be rotated, producing dark bands on a gray field. The separation of these bands is altered continuously by the rotation of the gratings. Hence there is produced a mobile acuity measure and a device which gives small variations in acuity.

Influence of Age and Sex on Visual Acuity

One would expect that visual acuity would gradually decline with increasing years. Donders and deHaan assert that from the thirtieth year on, visual acuity sinks one-tenth for every ten years and that between the fiftieth and sixtieth years as much as two-tenths until, in the eightieth year, it may be only one-half normal. The visual acuities as determined by deHaan for each decade are:—

Age	Visual Acuity
10	1.18
20	1.15
30	1.1
40	1.03
50	0.94
60	0.83
70	0.70
80	0.55

This law of deHaan has not, however, been generally accepted as being correct. H. Cohn examined one hundred persons more than sixty years of age and found the decrease in visual acuity to be extremely slight. Boerne and Walther examined over four hundred persons and found that in the healthy eye there was a slight and uniform decrease in acuity from the fortieth year on, but that the acuity in the eightieth year period was of the order of 6/9.

Bordier carried out an extensive series of researches on this question and obtained a set of data which, when plotted, shows a decrease of acuity with increasing years after the manner of deHaan, but the whole level of acuities was higher. Bordier's work seems to clearly indicate an increase in acuity from five up to fifteen years of age; at about fifteen years the average acuity is rated the highest. Also, his experiments show that, on the average, the normal acuities are higher for men than for women and that the maximum point is reached at an earlier age in life for females than for males. It may be worth calling attention again to the fact that visual acuity is normally at its best between fifteen and twenty years of age: therefore we should expect in our clinical work to take due regard and cognizance of our experimental data and the age of the person under test.

Influence of Pupillary Diameter upon Visual Acuity

The variations of the size of the pupil exercise two effects—which are opposed the one to the other—upon the visual acuity. The pupillary dilatation increases the visual acuity in that it reinforces the luminous intensity of the retinal images; but, by virtue of its participation in the formation of these images in the eccentric portions of the retina, it diminishes their sharpness and therefore reduces the acuity. Hence the pupillary contraction which is favorable to the sharpening of the retinal images diminishes the luminous intensity; it follows, therefore, that the pupillary contraction will increase the visual acuity if the surrounding luminosity does not fall below a definite amount. Likewise, if an ametropic eye is not corrected, the influence of the diameter is considerable, for the diameter of the diffusion circles is proportional to the diameter of the pupil. The chief difficulty in determining the influence which the size of the pupil of an emmetropic eye has upon the visual acuity lies in the exact experimental determination of the apparent size of the pupillary diameter, for if this can be found the real dimensions thereof can be obtained by calculation. Bordier, by a series of ingenious experiments, determined the apparent pupillary diameter by the aid of instantaneous photography; the visual acuity was monocularly determined for a given value of the size of the pupil. Various devices were employed to obtain large pupils; darkened rooms with charts illuminated by light reflected from external sources carefully screened from the observer were used. The results of Bordier's experiments are given below:

Apparent diameter of pupil	Real diameter of pupil	Corresponding visual acuity
2.06 mm. (daylight)	1.8 mm.	2
4.48 (average illumination)	3.9	1.85
4.65	4.04	1.8
6.9	6	1.75
9.58	6.8	1.70

It is obvious, therefore, why objects which are seen dimly become more distinct when viewed through a stenopaic disc, since the aperture, being smaller than the pupil, diminishes the circles of diffusion. This is the reason why myopes see better at a distance through a small opening. Such an opening can, as a matter of fact, be used as a magnifying glass: the object which is to be examined can be moved close to the eye and large retinal images thus obtained.

Broca has given the results of some investigations on the contraction of the pupil and the resulting loss of illumination caused by placing various sources in the direct range of vision. The well-known effect of lamps placed in the field of view is to cause the pupil aperture to contract with the result that the luminosity of other moderately bright surfaces is enormously reduced and they appear very dark in comparison with the source from which their brightness is derived: indeed, for this reason, a bright lamp placed between the observer's eye and the object illuminated may even render it impossible to distinguish the latter at all. The following, for example, represents the contraction of the pupil and the resulting loss of illumination when various light sources are put in the direct range of vision:

Lamp	Pupillary diameter	Fraction of light used
No source in field of view	12 mm.	1
Incandescent lamp	8	0.43
Mercury lamp	6.8	0.32
Arc lamp in globe	6.7	0.25 – 0.34
Naked arc lamp	5.7	0.22

It will be seen, therefore, that the apparent gain in illumination following the use of a high illuminant is soon lost owing to the fact that it causes a marked contraction of the pupil; hence the use of bright sources in the direct line of sight is not only of marked inconvenience to eyesight but it is not even economical.

Recently Cobb has published the results of some investigations upon the influence of pupillary diameter upon visual acuity. One of the functions of the pupil is that of compensating for the defects of the refracting system of the eye. By a reduction of the size of the light-pencil the area of the diffusion circle is decreased and the image is sharpened, the effects of chromatic and spherical aberration and of regular or irregular astigmatism being partially eliminated or diminished. It is, however, a well known fact of physical optics that, owing to diffraction at the margins, the aperture of an optical system places a limit upon the resolving power of a system. From his experiments Cobb concludes: (1) By the use of circular diaphragms before the eye it is shown that an aperture for optimal visual acuity exists somewhere between the limits of 1 and 5.6 mm. for brightness of test-object between 5.9 and 189 candles per square meter. (2) When the illumination of the test-object is compensated for the size of aperture to give equally illuminated images upon the retina, the optimum is somewhat less than when the test-object is constant and the illumination of the image depends upon the pupillary area. In the former case it falls on the average at 2 to 4 mm., in the latter at 4 mm. Similar differences are shown in the case of each of the observers, but those having on the whole the highest visual acuity show also a larger optimum pupil. (3) With an aperture of 1 mm. diameter the observers give almost identical results, which agree closely with calculated results. (4) The optimum pupil corresponds on the whole with the size of pupil accepted as normal for all except extreme conditions: 2.8 to 4 mm. From this lower limit up to 5.6 mm. the variations in visual acuity with size of aperture are not large enough to be of practical importance. (5) The tabulated experimental results obtained from Cobb's curves show:

Brightness Compensated		Constant brightness of 189 candles per sq. meter		Constant brightness of 5.92 candles per sq. meter	
Diameter of Artificial Pupil	Relative Visual Acuity	Diameter of Artificial Pupil	Relative Visual Acuity	Diameter of Artificial Pupil	Relative Visual Acuity
1	4	1	4	1	3.5
1.4	5.3	1.4	5	1.4	4.45
2.0	6.7	2.0	6.05	2.0	5.25
2.75	7.1	2.75	6.05	2.75	6.00
4	7.2	4	6.10	4	6.15
5	7.0	5	5.8	5	5.80
5.60	6.8	5.6	5.75	5.6	5.70

These investigations show quite clearly that eyes having equality of functions and structure in all particulars, and yet varying widely in pupillary area will have quite appreciable acuity differences. Doubtless, in the case of large pupils, the effects of spherical aberration enter markedly. In our work of testing, therefore, it seems best to keep the test rooms sufficiently lighted to cause an approach toward pupillary contraction ordinarily existent. Also, we have to handle eyes with very small pupils at one time, and at other times find eyes with very large pupils. Very often we find —and our textbooks lead us astray on this point somewhat —large pupils in conditions of myopia and we may frequently find what we may judge to be some degree of constriction of pupillary opening in cases of hyperopia. If such is so, then the tendency would be to slightly overcorrect myopia and undercorrect hyperopia if this were the only factor entering in.

Influence of Retinal Adaptation on Visual Acuity

It was discovered by deHaan and Piekema that there were noticeable differences in the visual acuities of their eyes under the same lighting conditions which apparently depended upon variations in the retinal adaptation. Broca has since investigated this phenomenon in some detail. He used an apparatus carrying either a black screen, in order that darkness adaptation conditions might be produced, or a white screen, suitably illuminated by an auxiliary light source the distance of which from the screen could be varied, which served as an adaptation center. The brightness of the source was then compared with that of the aerial image of a test-object of known brightness. An artificial pupil of 2 to 2.5 mm. was employed to eliminate the influence of the pupillary diameter and thus obtain the true effects of retinal adaptation upon the form sense. Broca's results indicate:—(1) for low intensities of illumination the visual acuity increases with darkness adaptation, (2) for average luminosities the visual acuity remains the same whether the retina is adapted or non-adapted, (3) for high intensities of illumination the visual acuity decreases with darkness adaptation.

Influence of Luminous Intensity upon Acuity

In general, the visual acuity increases when the illumination is increased and diminishes when its intensity is decreased. In investigating the visual acuities which correspond to different luminous intensities it is indispensable to obtain a "dark adapted" retinal condition. The visual acuity depends directly upon the illumination of the chart, but it is difficult to determine the relation in a precise manner since there are many factors which may affect it. The influence of the adaptation of the eye we have already mentioned; the pupillary size, the manner of contraction of the pupil and degree of optic perfection all exert an influence. Aubert, in 1865, determined the surface of the aperture in the window of a blackened cabinet which would permit of the reading of the different lines of Snellen type at a distance of one meter; from his results he was able to calculate the relation between the luminous intensity and the visual acuity. Carp used smoke glass of various depths of shade of known absorption power. He found that ordinary daylight can be reduced to 0.05 of its normal amount without causing a diminution in the visual acuity of emmetropes; in the case of myopes and of the aged the visual acuity diminishes more rapidly, for a reduction to 0.12 of diffuse daylight produced a diminution in the acuity. Druault utilized artificial illumination in his measurements; his method consisted in moving a candle toward the test-chart and noting the distances at which the light would allow each line to be read, the eye being in a state of medium adaptation. All methods of observation and experimentation show conclusively that the visual acuity increases at first quite rapidly with small changes in the illumination but that finally a very large increase in luminosity is demanded in order to change the acuity by a small percentage.

Piekema and Laan investigated the influence of illumination upon acuity by taking every possible precaution to exclude perturbing influences due to retinal adaptation. They reduced their observations to curves in which the abscissas represent the acuities and the ordinates the luminous intensities expressed in meter-candles. These curves show that, while the visual acuity of one experimenter was practically double that of his collaborator, yet both sets of data indicate the same general effects of the intensity of illumination upon the visual acuity. Experimentation also indicates that the increments in acuity corresponding to small changes in the illumination are very much less for the non-adapted retina. These relations between acuity and illumination for a single eye are modified somewhat when binocular vision is enjoyed. Nicati and Macé de Lépinay, and Snellen have investigated this question as well as the influence of diaphragms upon monocular and binocular vision. Their results show that the acuity-luminosity curves for binocular vision are of the same shape as those obtained for one eye only but give, as is commonly known, higher acuities binocularly than monocularly. The influence of apertures is seen to be most marked when the intensities of illumination are feeble; this is obvious since the pupils will be large under low illuminations, while the apertures of the diaphragm will be small in comparison.

We may, therefore, conclude in a general way that different methods and test-objects yield different absolute results but the relation between visual acuity and brightness of the background is in general the same. It is seen that when the brightness of the background is low the visual acuity increases very rapidly with increasing brightness of the background; after the brightness has reached a certain value, *e.g.* when the illumination has reached an intensity of one foot-candle, the visual acuity increases very slowly with increasing brightness of the background. The relation for ordinary intensities may be thus expressed:

$$\text{Visual acuity} = k \log I$$

in which k is a constant and I is the intensity of illumination. Experimentation shows that the value of k is not the same in the low and medium regions of illumination.

Visual Acuity in Lights of Different Colors

In his experiments upon the influence of the intensity of illumination upon the visual acuity Cohn made some observations using monochromatic light sources and found that the visual acuity attained a maximum value under yellow light. Under an illumination of 36 meter-candles he obtained the following results:

Light	Visual Acuity
White	2.
Yellow	2.15
Red	2.00
Green	0.66
Blue	0.37

Macé de Lépinay and Nicati as collaborators and Uhthoff came to the conclusion that it is possible to attain the same visual acuities with any color of illumination provided sufficiently high intensities are employed. The first two of the above named experimenters studied the visual acuities in the different colors as a function of the objective luminosity; they concluded from their curves that the acuity is the same for all radiations of wave-length greater than 5070 t. m. when taken in conjunction with the Purkinje phenomena. Taking as a unit for each color that luminous intensity which gives a visual acuity of 0.33 they obtained the following results:—

Visual Acuity	Intensity of Illumination				
	λ=5070	λ=4970	λ=4580	λ=4420	λ=4280
0.47	5.00	8.18	....	....	....
0.42	2.67	3.71	5.48	6.51	....
0.33	1.00	1.00	1.00	1.00	1.00
0.26	0.48	0.38	0.22	0.21	0.18
0.22	0.33	0.23	0.13	0.12	0.10

It will be seen, therefore, that the visual acuity increases and decreases more slowly for the colors having short wavelengths than for the less refrangible radiations for any given variation in the objective luminous intensity and that this difference is all the more accentuated when one has under consideration radiations which are more refrangible than 5070 t. m. The luminous intensity can vary considerably in the blue without appreciably influencing the visual acuity. And, again, if a test object is lighted in turn by different portions of the same spectrum it will be found that the clear recognition of the object is due solely to the illumination furnished by the less refrangible portion of the spectrum.

We know that the eye is not chromatically corrected, with the result that the image of an object illuminated by light of rather wide spectral limits is not sharply defined upon the retina. Bell has compared the acuity of the eye in tungsten and mercury arc lights and has obtained results indicating an advantage for this latter illuminant: this is probably to be attributed to the more nearly monochromatic character of the light from the mercury arc. Luckiesh has confirmed these results and extended them, using lights of the same color but differing in spectral character; this is possible through the employment of proper absorbing solutions. Some of the results of Luckiesh are given in the subjoined table; it is to be remarked that "his data, except in one case, were not obtained by the method of using fine detail at the limit of discrimination but instead in terms of equal readability of a page of type, which proved after some practice to be a rather definite criterion."

Relative Illumination for Equal Readability

Case	Source	Color	Approximate Foot-candles	Relative Illumination
1.	Mercury arc	Green line	2.0	1.00
	Tungsten	Green		1.75
2.	Tungsten	Yellow	4.0	1.00
	Tungsten	Yellow (diff. shade)		1.33
3.	Sodium line	Yellow	0.5	1.00
	Tungsten	Yellow		1.66
4.	Mercury arc	Green	0.5	1.00
	Tungsten	Green		5.10

No stress can be laid upon the accuracy of the absolute values given above but these and similar results from other experimenters make it conclusively evident that monochromatic light is superior for discriminating fine detail.

It has been found that monochromatic light is superior to daylight for such discrimination. The acuity on the Snellen scale, for instance, was found to be 1.11 and 1.28 respectively for daylight and monochromatic green light of equal intensities; another experiment showed that for a visual acuity of 1.28 on the Snellen scale the intensity of illumination with daylight or with tungsten lamps was nearly three times that required for the same visual acuity with monochromatic green light. As the brightness of the background was increased it was found that the difference in visual acuity under a given illumination of tungsten light and monochromatic light decreased. Luckiesh has recently conducted a very thorough-going series of experiments for determining the visual acuity in monochromatic lights. His investigations indicate that monochromatic lights differ in their defining power and that yellow monochromatic light is superior to others in this respect. It was also found that for any given change in brightness of the test-object the change in visual acuity was least for yellow monochromatic light.

Visual Sensitiveness and Acuity

By the term visual efficiency is meant the ratio of the service rendered to the eye to the expenditure of nervous energy. The proper maintenance of visual efficiency demands attention to two important factors, *viz.:* the sensitiveness of the eye to differences of luminosity and, second, the acuity of the eye. It is found that both the sensibility and relative visual acuity, when considered with reference to illumination, assume an asymptotic relation after passing a luminosity of one lumen per square foot. This may be summarized into a working principle by which the degree of illumination required for any surface to meet the ordinary optical requirements may be ascertained, to wit: the illumination of any surface requiring the continued application of the eyes shall be such that the light reflected or transmitted by it shall be equivalent to a luminosity of approximately one lumen per square foot. Inadequate luminosity and excessive luminosity of the direct field of view are about equally undesirable. In the former case the retinal images are not distinct and the eye grows fatigued in its efforts to sharpen their perception. Excessive brightness produces images which are intensely bright causing injury to the retina. Optical and engineering specialists differ in their estimates of the safe maximum of intrinsic brilliancy for direct vision; the values range from 1.75 to 5 candle-power per square inch of apparent light source.

There are, in conclusion, many physiological conditions and ocular derangements which affect visual acuity. Also, there are important relations existing between the refractive condition of an eye and its visual acuity, for we know that ametropic errors are of axial, curvature or indicial cause and that correcting lenses do not produce the same sized retinal images in an error of the same degree but due to a different cause. A discussion of these would lead us afar, for the purpose of this paper has been to call attention to the physical factors which cause acuity determinations to be modified or affected.

Abstracts and Reviews

The Response of the Average Pupil to Various Intensities of Light

Prentice Reeves

FOR EACH brightness level used the pupil has a different diameter, as the pupil is automatically adjusted so as to tend to maintain constant light energy on the retina. That is, when the intensity of illumination is increased the pupil contracts and *vice versa*, or if the distance between the eye and stimulus is changed, the pupil is also changed to keep the retinal illumination constant. The procedure cited by Blanchard (*Physical Review*, No. 11, 81, 1918), on the consensual reflex, *i.e.* the effect of exposing one or both eyes to the light,

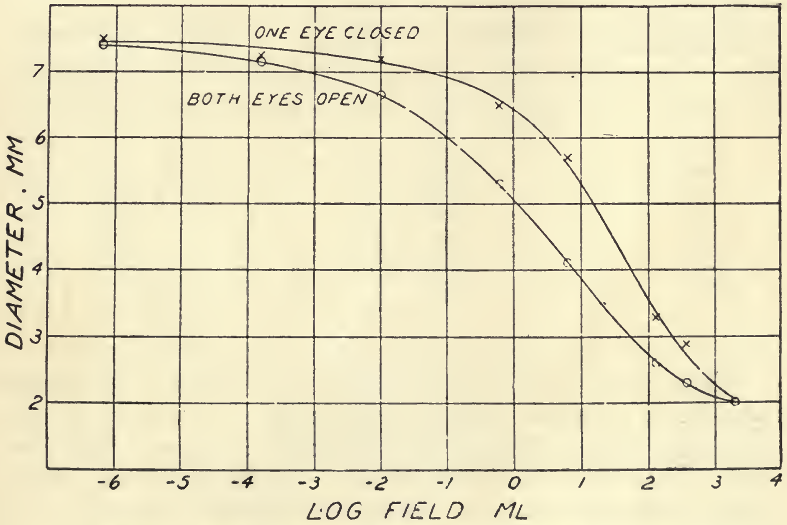

Figure 1. Relation between brightness and diameter of pupil.

was repeated. The shapes of the various curves are the same as those of Blanchard. The eye and the millimeter scale in the plane of the pupil were simultaneously photographed by flashlight. The procedure was repeated for several brightness levels varying from total darkness to a just tolerable reflection of direct sunlight from white drawing paper. The effect of exposing one or both eyes was studied. Figure 1 and the data in Table 1 show the results obtained from one of two subjects. It will be seen that in the range of ordinary intensities there is a marked effect of closing one eye. From these results it is seen that the amount of contraction of the pupil for brightness in excess of 100 millilamberts is slight. In getting data on the very contracted pupils a motion picture camera was used.

TABLE 1

Effect of Closing One Eye on Pupillary Diameters

Brightness in millilamberts	Log B	Both Eyes exposed		One Eye closed		Difference	
		J. B.	P. R.	J. B.	P. R.	J. B.	P. R.
0.	Taken as—6.0	7.4	8.6	7.5	8.6	0.1	0.
0.00015	—3.82	7.1	8.5	7.2	8.5	0.1	0.
0.01	—2.0	6.7	8.3	7.2	8.5	0.5	0.2
0.6	—0.22	5.3	7.0	6.5	7.8	1.2	0.8
6.3	0.8	4.1	4.3	5.7	5.9	1.6	1.6
126.0	2.1	2.6	2.9	3.3	3.3	0.7	0.4
355.	2.55	2.3	2.4	2.9	2.9	0.6	0.5
2000.	3.3	2.0	1.9	2.0	2.0	0.	0.1

When changing from one brightness to another the retinal sensitivity changes and has been shown to occupy an appreciable period of time for even slight changes in illumination. This consists of two factors—a retinal process (whatever it may be) and the change in pupillary diameter. To determine the rate of closing of the pupil, the motion picture

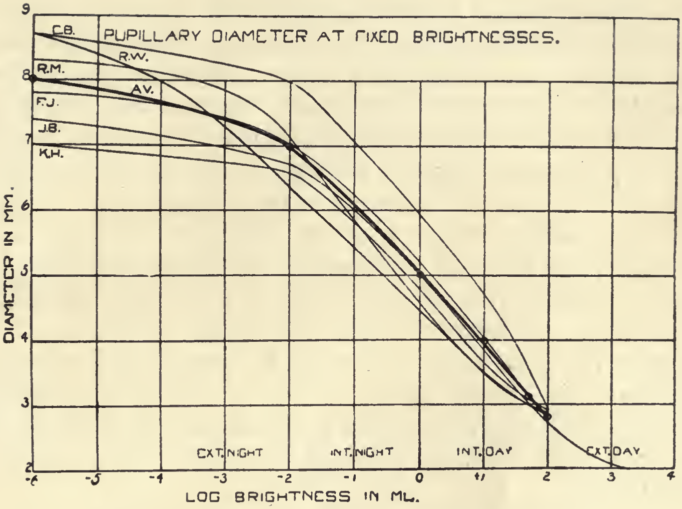

Figure 2. Pupillary diameter at fixed brightnesses.

camera was driven by a controlled motor so as to take a picture every tenth of a second. The subject was fixed in the head rest as before, and after being fully dark adapted so as to obtain a maximum pupil the camera was started, the

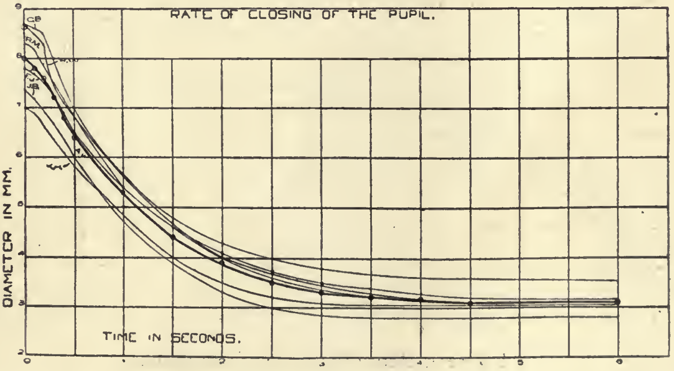

Figure 3. Rate of closing of the pupil.

taking light turned on and pictures were taken as the pupil closed from its maximum to its minimum diameter as chosen. The results on six subjects show that the average pupil reached its minimum in less than 5 seconds and the greater part of the contraction occurred within the first two seconds. Figure 3 gives the data on the rate of closing of the pupil.

In order to get data on the rate of opening of the pupil, it was necessary to use a rather elaborate electrical device for regulating time for adaptation and putting on the taking lights in time to photograph the pupil after the required time in darkness. Figure 4 shows the results obtained. (The average rate of closing of the pupils examined is shown by the heavy line in the figure.) The conclusion is drawn that "the opening of the pupil to a maximum diameter requires as many minutes as it required seconds for it to close to a minimum."

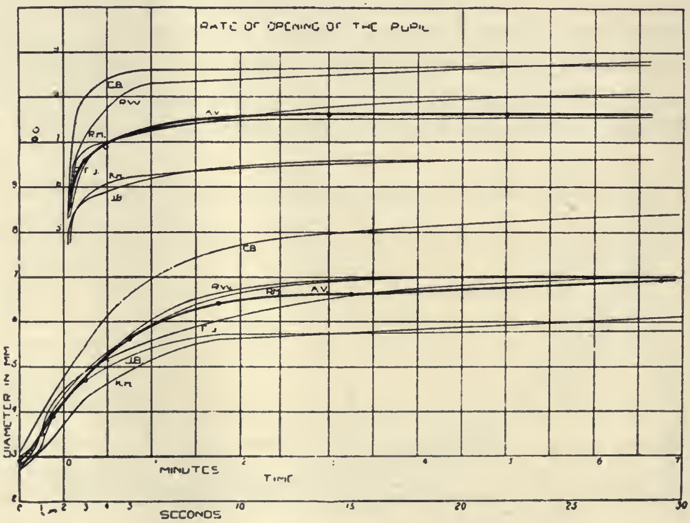

Figure 4. Rate of opening of the pupil.

In the author's experiments the data were obtained by changing from one definite brightness to another—darkness and 100 millilamberts. Different results could be obtained if any other brightness ranges were used.

In experiments where it is essential to know the light energy striking the retina the diameter of the pupil is an important item.

(Abstracted from *Journal of the Optical Society of America*, Vol. IV, page 35, 1920.)

A New Apparatus for Testing Accommodation

Captain Harvey J. Howard

THE AUTHOR states that the test producing results subject to the greatest variation is the test for the near point of accommodation. These discrepancies may be caused by any one of these several different factors: (1) Difference in the size of the test objects; (2) Difference in the speed of approach of the test object; (3) Difference in the illumination and legibility of the test letters; (4) Difference in the place of contact and the angle of the measuring rule; (5) Difference in the position from which the reading is computed; (6) Difference in the instructions to the subject; (7) Difference in the personal equation of the examiners; (8) Difference in the personal equation of the subject.

Two methods of testing are indicated. The first of these may be referred to as the *subjective* test, *i.e.* the applicant is required to indicate, while the test card is approaching the eye, the first blurring of a letter. In making the *objective* test, it is necessary to use letters and figures, and the test card must be held so close to the eye that the letters are unrecognizable and then slowly carried away until they first become legible. Unless the subject knows the letters it must be considered an objective result the moment he reads them correctly.

The approximation or subjective method calls for the location on the diopter measuring rule of the first blurring of a letter or object. If the card is gradually brought further in, the letters finally become illegible. The result accepted quite generally by this subjective method is not the point of the first illegibility but the point of the first blurring noticed.

The recession or *objective* method requires the card to be held close to the eye at the beginning and carried slowly away until the letters become legible. The position on the rule where this first legibility occurs is not the same as the point of illegibility by the approximation method. But as a matter of fact, attested by a number of experiments, the point on the rule indicating the first legibility by the recession method is the same or practically the same point as that indicating the first blurring by the approximation method. The difference in the two was found to be astonishingly small—in some individuals less than 1 mm. of actual measurement. With these results before us, the problem is made easier.

The apparatus described by the author consists of four essential parts: (1) A hood with an observation aperture for one eye; (2) A rule attached to the hood, measured off in millimeters and diopters; (3) A test object carrier; (4) A set of test letters and test objects.

The remainder of the paper is devoted to a detailed description of the apparatus embodying the four above mentioned essentials.

(Abstracted from the *Archives of Ophthalmology*, Vol. XLIX, page 182, 1920.)

The Maddox Multiple Red Rod

A Consideration of Some of Its Optical Defects

Captain Percival Dolman

DURING the course of a series of experiments made for the purpose of investigating the accuracy of the Maddox rod test, it was discovered that the line of light often appears nearer than the light which is located six meters away. The statements of a number of observers have repeatedly verified this fact.

When the line is in sharp focus, it is seen as a bright band of light, of uniform density, with sharp, clean-cut edges. Such a line appears to be located at the same distance as the light. When the line is not in focus, it is seen as a wider band, of unequal brightness, with hazy, irregular edges. The general effect is that of indistinctness. The line then appears to be located often only a few feet from the eye.

The influence on the Maddox rod test of this false localization of the line is in favor of the measurement of an excessive amount of esophoria. The appearance of the line of light, therefore, has a direct bearing on the accuracy of the test.

The same indistinct appearance of the line may be caused by certain optical defects in the Maddox rod. An examination of the several rods which were being used at the time, disclosed such a high percentage of defects that a special investigation was begun to determine the optical qualities of other Maddox rods in general use. The results of that investigation form a part of this report.

Twenty multiple red rods were examined. Some of them were in use in the laboratory, others were found in nearby clinics, and a few were obtained from dealer's stock. The defects found in these rods are of two types, involving: (1) the character of the line of light and (2) the presence of prism acting to deflect the line of light from its true position.

The prism is readily detected by holding the rod before one eye so that a horizontal line of light is seen while the other eye looks at the light. The position of the line in relation to the light is observed. Then the rod is rotated through 180 degrees just as a cylinder is rotated in the trial-frame. The line is again horizontal and, if no prism is present, will be in exactly the same position in relation to the light as at the first observation.

An inspection of the twenty multiple rods showed that 50 per cent formed a line of light defective in character and apt for this reason to give an inaccurate result in the test. Eleven rods (55%) contained an amount of prism ranging from one-half to one prism dioptry. Six rods (30%) were found to be free from all defects.

Ten single, clear glass rods were inspected and all but one found to form a line of light of acceptable character. The one exception formed an indistinct line, variable in width and of unequal density. No prism deflecting the line was found in any of these single rods.

The accuracy of the Maddox rod test is affected by the prism only when its base is so located that the line of light is deflected at a right angle to its direction.

The manufacture of multiple red rods involves several highly technical processes and the finished product is probably as good as can be expected. It should be possible to supply them free from any prism but the removal of optical defects from the corrugated surface is a problem that will not be easily solved. Some of the responsibility for the condition exposed in this report may be shifted to the popular demand for a colored multiple rod. The test can be accurately made with a clear glass multiple rod and a colored glass may be used with it if a colored line of light is desired.

(Excerpted from the *Archives of Ophthalmology*, Vol. XLIX, No. 2, pages 194–197, 1920.)

The Optics of the Cornea

George W. Vandegrift, M.A., M.D.

THE CENTRAL zone of the cornea, which is essential to vision, has an approximate diameter of 4 mm. The pupillary width frequently varies up to 6 mm. under which condition the peripheral area may cause spherical aberration and increased size and distortion of diffusion circles and of astigmatic focal lines. The central area is the section of a sphere having a radius of 7.75 mm., as a fairly constant average. The author, using a Javal-Schiötz ophthalmometer, determined the outline of the central visual zone as about 35 degrees horizontally and 30 degrees vertically, which is slightly larger than found by Erikson.

The peripheral zone was analyzed and the curvature found not only to change abruptly at the border of the peripheral zone, but to increasingly change horizontally and vertically as far to the external periphery as the ophthalmometer would furnish distinct readings.

(a) In seven cases in which the central zone was non-astigmatic a 0.50 to 1 D of astigmia developed at about 15° which in common parlance was with the rule, that is, a decrease of horizontal curvature.

(b) In thirty-one cases of hypermetropic astigmia with the rule an increase of 1 to 2 D developed.

(c) In eight cases of myopic astigmia with the rule the astigmia increased 0.50 to 1 D.

(d) In one case of hypermetropic astigmia 0.50 D with the rule the astigmia in the peripheral zone became against the rule 2 D, an increase of curvature.

(e) In one case of myopic astigmia with the rule 1 D the periphery displayed no astigmia.

(f) In two cases of myopic astigmia of 1 to 2 D against the rule one displayed no astigmia and the other 0.50 D of similar astigmia 15°.

In all cases except (e) the change of curvature that began at about 15° from the fixation line persisted increasingly to the periphery.

The peripheral zone of the anterior corneal surface approximates a parabola. This may be readily demonstrated by the ophthalmometer as the images of the mires, which are rectangular at the central zone, continuously elongate within the peripheral zone. Because of the parabolic form the peripheral zone produces positive aberration which, in certain cases such as enlargement of the pupil either natural or artificial and aphakia, interferes with distinct vision.

Considerable data and information of value (although not new material) are given on: (1) the refractive power of the posterior surface of the cornea, (2) the positions of the cardinal points and their influence and use as well as the effects of accommodation upon them, (3) a general discussion of astigmia and (4) the corneal reflexes.

In speaking upon the wearing of astigmatic corrections the writer says: "The form of the retinal image produced by an astigmatic cornea, whether the defective curvature is horizontal, vertical, or oblique, is not difficult to construct by placing an imaginary retina at various points on the optic axis. These retinal images are distinctly different from those formed by axial ametropia for in the latter the matter is one of size and definition, while in the former it is one of angular distortion, for the image formed by the defective curvature is larger (hypermetropic astigmia) or smaller (myopic astigmia) than that formed by the opposite curvature. Nor does the wearing of the proper correcting cylinder remove the difficulty fully, for when placed at the anterior focal point a cylinder lens defines the image, but does not affect its size, a result that can be attained only by placing the lens in direct contact with the cornea. It is for this reason that even after proper correction with spectacles patients may continue to complain of image distortion or more rarely of monocular diplopia symptoms, which, however, usually are transient as the astigmatic error is slight compared with the entire ocular refractivity.

"When astigmia is considered binocularly the law of corresponding retinal points intrudes for if the astigmia is asymmetric and particularly asymmetrically oblique the images fall upon dissimilar retinal parts, for each image is displaced toward the meridian of greatest curvature. Under such an exigency binocular diplopia may result unless correcting cylinders are worn. Without such correction diplopia must be overcome by sectional ciliary action, which is doubtful, or by exertion of the fusion power through contraction of the oblique muscles rotating the eyes about the anterior-posterior axis, maintaining binocular single vision."

(Abstracted from *Archives of Ophthalmology*, Vol. XLIX, pages 421–429, 1920.)

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Illumination as a Factor of Importance in Dealing with Eye-strain

Frederic A. Woll, Ph. D.

ILLUMINATION, natural or artificial, may cause eye-strain by being too bright or intense, by being not bright nor intense enough, or by being improperly placed.

When light is too bright or too intense, the pupil of the eye contracts out of proportion to the amount of convergence and accommodation that is being used, the lid muscles contract, and the effort to see beyond or through the light becomes a strenuous one. If it is necessary to continue the effort for any length of time, other facial muscles are involved until ease and comfort give way to pain, headaches, and discomfort. When light is not bright nor intense enough, the pupil of the eye dilates out of proportion to the amount of convergence and accommodation used; the muscles of the lids and certain facial muscles are called into use and the usual reflexes manifest themselves. When light is poorly placed, the pupil will either contract or dilate out of proportion to the convergence and accommodation used involving the use of the other muscles. In the first case an attempt is being made to shut out light; in the second case an attempt is being made to get more light; and in the last case, it may be either one of the two. In any of the cases, however, the effort to see becomes mostly an extreme muscular one. That effort causes a fatigue which at first is acute, and finally chronic, if no relief is given.

At the present time we are troubled more with too much illumination than in the days that have gone by. At one time when candles, oil lamps, and flickering "fish-tail" gas burners were used, we suffered because of an insufficient amount of light. Today, we have swung considerably in the direction toward what might be called over-illumination. All eyes seek the light whether they belong to the fluttering moth or to the steady human. And so, though the light does hurt, we go toward it until we feel pain. We like everything bright and shiny, so we illuminate room, house, store, and office beyond what is actually needed for the purpose of obtaining easy and comfortable vision. Some persons need more illumination than others; some can stand more than others. What is not enough light for one person may very easily be too much for another. The threshold of vision varies with illumination, temperament, sex, age, health, the kind of work, the object under scrutiny, and the ocular refraction.

In estimating the amount of illumination that is needed for any given room certain rules are followed. Though those rules are not based on an entirely arbitrary judgment, yet they are likely to result in an illumination which is not based on real eye-sight needs. Eye-sight needs require more than mere illumination as such. Reflecting surfaces, direction of light, shadows, angle at which the work is held, conflict of sources of light, secondary sources of light due to reflection, irradiation, and error of ocular refraction, corrected or uncorrected, all enter into the problem. Many times the illumination is all that may be desired so far as the illumination itself is concerned, but the other conditions, or some of them, have not been considered. Too often the illuminating engineer believes his work is done when he is able to procure certain results. The room is bright, there is a minimum amount of shadows, and the light is well distributed. But the questions that should be asked are: Is the room to be used by workers, and if so, what kind of work are they going to do? How are the workers to be placed? Who are the ones that require more light than the average? Are the ocular defects of the workers corrected? Are they working with reflecting surfaces? Are those reflecting surfaces so placed at an angle that they will not become secondary sources of light and interfere with easy, unstrained, and unconscious vision? Are colors used? What are those colors? Do they present polished, glazed, or dull surfaces to the eye? These are factors which must be seriously considered, and they must be given thorough attention. At this point the eye-sight specialist must function and not the engineer alone. Unfortunately, however, too often neither is consulted. Sometimes after a conference with those two experts, it is decided that the necessary changes are too costly. Eye-strain produces first a local fatigue and later a general fatigue. When our eyes are tired, we are tired all over. A tired worker is not an efficient worker, nor a happy worker. Money saved at the expense of eye-sight or human efficiency is not a wise saving.

A short time ago, the writer was stopping at a prominent hotel in St. Louis. The manager discovered that the illumination in his hotel was not as good as the illumination in other hotels in his city. Contrary to best advice of the illuminating engineers, he installed a lighting system that was much too bright or intense. His reason was a purely arbitrary one. He claimed that his guests wanted plenty of light. He insisted on giving them what he thought they needed or what he thought they wanted. The result was that many of his guests felt entirely comfortable—when they wore smoked glasses or eye shades. His system of indirect lighting was entirely faulty. The ceilings were too bright and became secondary sources of illumination that were as conducive to eye-strain as an uncovered source of illumination. In his own office, however, he had good illumination though his secretary stated that she felt as if she were either in a sick room or else at a "wake." She said that she often felt that she was simply groping her way about the room. It is evident that the manager in his attempt to suit others according to his own ideas and to suit himself according to his needs, swung from one extreme of the pendulum to the other. The engineer would undoubtedly have helped him reach at least a happy medium had he been willing to heed the advice that was offered.

The architect, the decorator, and the artist often in their attempt to produce artistic effects succeed in producing undesirable results so far as illumination is concerned. Shadows are produced. Parts of a room are placed in semi-darkness in order to bring to light a piece of statuary or a painting. That effect may be desirable for the sake of art. In order to get a closer view of such a piece of statuary or a painting, one has to carefully and cautiously feel the way step by step. The room is kept quiet and mysterious by the kind of illumination that is only too often used by the artist. Yet there is no need for having an illumination that has such an effect.

The day for the uncovered light is all but past. It is still found, however, wherever more illumination is needed in order to see some special kind of work. An example is to be found in the factories, machine shops, the typewriters' rooms, and other similar places. The "drop light" is all too handy. If it is used at all, it should be hooded in such a way that the worker will not be compelled to look at his work beyond or through the light of the lamp. It should be placed also with reference to shadows and reflections. Accidents have often occurred because of an improperly placed "drop light."

Another example is to be found in many homes, especially in the hallways. Sometimes it is not easily possible to see into the space beyond the light. Irradiation resulting in so-called glare is the cause.

Still another example is the uncovered arc, incandescent or other form of electric lamp used for the purpose of illuminating highways and streets. It would seem as if the prime object of the municipalities was to illuminate everything except the highways, roads, or streets. Street illumination is primarily for the users of the roads and the streets. Why then is it necessary to illuminate the sky, sky-line, or buildings of the city, town, or country above ones natural line of vision. Those who drive or have driven at night know how extremely difficult it is to see beyond the illuminating source. The street lamp should be hooded and in such a way that it will not illuminate anything but the street below. Night driving and night riding will then become less fatiguing than it is now, and there will be also fewer accidents. Illuminating engineers need not devote their entire time to interiors. More attention should be given to outdoor illumination.

Indirect light is often placed too near the ceiling. The ceiling immediately over the lamp is then a secondary source of light which may easily be as fatiguing and conducive to eye-strain as a low candle power uncovered light. When placed too far from the ceiling it may bring the part of the room immediately under the lamp into a shadow and even darkness. There is a form of indirect lighting fixture which is so constructed that its opaque undersurface is indirectly illuminated. That form is probably the best form of indirect lighting. With it there can be few if any shadows, and the light will be diffused and evenly distributed. The one particular precaution that must be followed, however, is that such a fixture should not be supplied with a too high candle power lamp when it is evident that two or perhaps even more such fixtures supplied with low candle power lamps will give a more evenly distributed illumination. Here, again, there is an unwise saving practised. The purchaser often believes that the engineer is trying to sell more fixtures than are necessary. Often three fixtures properly placed and each carrying a fifty candle power lamp will give infinitely better results than one fixture with a two hundred candle power lamp improperly placed. The saving in current, in eye-sight, in eye-strain, and general fatigue will more than pay for the extra fixtures.

From the standpoint of eye hygiene, one may not say some forms of direct-indirect fixtures for lighting are better than others, but rather one may say that some kinds of fixtures are not as bad as some others. While the direct-indirect fixture is a partly covered illuminant, there is such a great variety of translucent globes that one can really assume that the difference between an uncovered illuminant and a direct-indirect fixture is a difference of degree only and not of kind. Many times the artistic figures with which the globe is decorated permit so much of the light of the high candle power lamp behind it to pass through that it causes a conflict between the object looked at and the source of light that illuminates it.

When the source of light is so placed that some of its direct rays enter the eye and fall outside of the fovea, it becomes a competitor of the object which is being viewed. The object viewed is not as bright as the source of illumination but its image falls directly upon the fovea and the impression is transmitted to the brain. The direct rays of the source are brighter than the object viewed and fall upon that portion of the retina which is better adapted for receiving impressions of lesser illuminated objects. That impression is also transmitted to the brain. The two impressions or stimuli struggle for the mastery. That struggle is experienced in terms of eye-strain. Sometimes this result is also produced by bright colors, contrasting colors, or glazed surfaces. Even the emmetrope will experience an unpleasant reaction under such conditions, and if he is more or less photophobic the usual eye-strain reflexes will simply be more apparent. The remedy, it is obvious, does not lie in the direction of lenses. In cases of ametropia there is added to the psychological conflict a purely physical effort. That effort is made in an attempt to overcome the ocular error of refraction because of the desire for better and clearer vision. If the error is of a small amount either its correction or the removal of the conflicting source of illumination will give the needed relief. In other words, one may say the eye (or individual) may be happy with either if the other is removed. In the higher powers of refractive error, however, both conditions will need correcting.

Flood lights, such as are used in the Union Station at Washington, D. C., and on the Singer Building in New York City, and in other indirect lighting systems, will give artistic effects and also sufficient illumination. There is, however, a psychological effect which is unpleasant and is confusing. That is the effect of contrast. The upper portion of the room, hall, hallway, corridor, or building is bright and clear, but the lower portion of the walls is in shadow. Those walls may have the necessary amount of illumination but by contrast appear dark and give the feeling or sensation of darkness or insufficient amount of illumination. The illusion causes strain nevertheless which can only be relieved by lessening the contrast.

Illumination, it is apparent, involves a consideration of something more than the mathematics necessary to determine the proper candle power for a given room or space. The defects, the reactions, the work and the varied needs of the human eyes are factors of great importance and they must be given due consideration always in any scheme of lighting.

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Perception of Colors and Movements with Foveal and Peripheral Regions of Retina[1]

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Introduction

IN PHYSIOLOGY and elsewhere one encounters the view that, although we cannot perceive chromas with the extreme peripheral retina, we can detect motion much better with it than with the foveal region. Some data gained from experiments, together with a little mathematical reasoning, compel me to oppose this statement in all of its phases. The contrary statements are:

1 In the great majority of cases any color that can be seen at the fovea can be seen also at the periphery of the retina, although for a shorter time at the periphery.

2 Some people, who appear to be hopelessly blind for certain colors at the fovea, can be made to see them in the same way that normal persons can be made to see chromas at the peripheral retina.

3 A type of mathematical reasoning applied to the supposed allusion of the swinging stick[2] shows that, if we fixate one end of the stick carefully and observe at the same time the other end of it, the indirectly observed end stimulates a greater streak on the retina and should therefore appear to move the faster or through the greater distance at each swing.

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[1] Some of the work reported in the present paper was started in the Psychological Laboratory of Harvard University, some of it was done in the Physiological Laboratory of Tufts College Medical School, but the greater part of it was done in the laboratory of Experimental Psychology of the University of Missouri.

[2] For this classical experiment, a stick with a white paper on each end is the essential part of the apparatus. By means of a string which is tied near the ends of the stick and caught at its mid-point by the hand of the experimenter, the stick is held in a horizontal position before the observer. The

4 Data gained in experiments to determine the judgments of the relative amounts and velocities of movement of objects in the peripheral and foveal fields of vision, show that the object must move either with a greater velocity or with a greater amplitude in the peripheral field in order to detect its motion as well as the movement of an object nearer the fovea.

5 If a small piece of paper on a large homogeneous background is moved through a given distance—for example ten centimeters—while the observer fixates a stationary point very near the paper, the actual extent of motion is generally underestimated. When the stationary point for fixation is farther away from the paper, the judgments are less accurate and the underestimations are greater. These estimations become more accurate as the point of fixation is shifted toward the paper.

A. Peripheral and Foveal Color Vision

Perception at the periphery. The apparatus used in this experiment was the perimeter which is pictured in Titchener's *Qualitative Manual*, page 10. The colors to be observed remain stationary while the eye follows the point which can be moved with different velocities toward the end of the board along the centimeter scale. It is also possible with this apparatus to flash a color suddenly on to the retina by merely placing it quickly behind the board so that it can be seen through the central hole.

When the observer carefully fixates a small spot on the

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observer is then instructed to keep his eyes on the paper at one end of the stick and at the same time to observe the paper at the other end. The stick is now set to swinging, and the observer is asked to determine whether the directly or the indirectly observed end seems to move the greater distance at each swing. Observers generally report that the indirectly observed end seems to swing through the greater distance at each pendular movement of the stick. In view of the circumstances that the angular velocities of all the points on the stick are exactly the same and that the indirectly observed end seems to move the greater distance, it has been assumed that we possess the tendency to overestimate the extent of motion of objects that move in the peripheral field of vision.

paper or even one at the edge of the hole on the board, the color finally disappears; if a point five centimeters to the right of the hole is fixated carefully, the color disappears much sooner; if the point of fixation is ten centimeters to the right of the hole, the color disappears much sooner; and when the direct fixation is considerably farther to the right, the color may disappear so readily that it is often difficult to notice.

As a slight modification of this experiment, the operator can move the fixation point slowly toward the end of the board, at another time more rapidly, and so on. The color disappears at a relatively short distance from the fovea when the movement is slow. Slow movement means better fixation, and observation teaches us that the better the fixation the sooner will either a directly or an indirectly fixated patch of color disappear. When the point is moved slowly, the red zone on the retina might measure ten centimeters in diameter on the perimeter scale. If the point is moved quite rapidly, the red zone might seem to be forty or more centimeters in diameter. Ordinarily, white and black are more persistently seen than red or any other color, but there are some exceptions to this.

If a patch of red is the object of peripheral observation and the fixation point is so far to the right that the red is not seen, it can be caused to appear by removing it for eight or ten seconds and then putting it back in place quickly. The observers for this experiment were about 190 students. Twenty-four of them were able to identify reds, greens, blues, and yellows better than black or white[3]. Nine of the total number of observers were able to see nothing but black and white with the extreme periphery, even though they could see colors well with the fovea; they were color blind at the periphery but not at the fovea. Ten of the total number of observers were blind at the periphery for reds and greens, but their foveal vision was normal. At unpredictable times two of the observers were blind at all portions of the retina for reds and greens, but more frequently for reds than for greens. It was so difficult to cause one observer to see either red or green with any retinal region that I felt justified in declaring the case one of typical color blindness to reds and greens.

Color perception by the color blind. The one observer who, in all ordinary tests, proved to be blind to reds and greens was tested carefully for his foveal and peripheral color vision in the same way that the normal observers were tested for their peripheral vision. Reds and greens of various tints and brightnesses were the stimuli employed. Four series of reds were selected. One of the series consisted of seven reds, all of which were brighter than a certain yellow which was selected as one of the contrast colors; these reds ranged from a reddish yellow to a reddish violet. Another series ranging from a reddish yellow to reddish violet was approximately as bright as the yellows. The third series was darker but not as dark as the violet which the observer could identify

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3 These results are very much in harmony with results reported by C. E. Ferree and Gertrude Rand, "The Absolute Limits of Color Sensitivity and the Effect of Intensity of Light on the Apparent Limits," *Psychological Review*, 1920, 27, 1-23. Instead of flickering the colors, these authors used lights of various intensities and arrived at the following conclusions: "The far periphery of the retina is not blind to red, blue, and yellow. It is merely deficient in sensitivity to these colors. That is, with stimuli of sufficient intensity the limits of red, blue, and yellow coincide with the limits of white light vision. * * * The blindness to green, however, is absolute," i.e. at the far periphery.

Since the year 1916 I have been teaching that, in general if the stimulus is intense, any given color can be perceived with all retinal regions. During the spring-summer term of the school year 1918-19 at the University of Missouri, I demonstrated this to my class in vision. In my investigations along this line, I found that approximately five percent of the observers were blind to red, green, blue, yellow or even white at the extreme peripheral retina and that the blindness to green was more frequent than blindness to red. The ratio was about nine blind to green to one blind to red. It was almost invariably the case (not always however), that an observer who was blind to green at the extreme periphery and not to both yellow and blue, can either see yellow with that region better than blue or blue better than yellow. If either blue or yellow can be seen poorly or not at all, the individual is almost sure to be blind at that region to green also. For several reasons these results are interesting but especially in view of the following facts: (1) That green appears in the spectrum only under the condition that blue and yellow overlap, and (2) that blue and yellow pigments in combination produce green. At present I shall not attempt to solve the problems raised here.

under ordinary conditions and which was accordingly chosen as the other contrast color. The fourth series was slightly darker than the violet. The significance of the contrast colors, yellow and violet, will be made clear in the following description of the method of procedure.

The subject, who was seated at the perimeter, was asked to look directly in the hole in the gray board. He was shown the yellow and the violet, after which a red was placed quickly on to the dark table so that the light rays from it passed through the hole and reached the retina of the observer. He was asked to make judgments quickly and tell which the color resembled the more, violet or yellow. Owing to the circumstance that there were twenty-eight reds of four different brightnesses, and also that they were not presented in a systematic order, the brightness factor was ruled out altogether and anticipation on the part of the observer would only have caused confusion.

The observer was able to name the colors accurately in terms of yellow and violet. He was much interested in the experiment because the colors which he saw were novel to him. He said that some of the colors resembled some effects which he had previously gotten while observing sky rockets and also when he looked at the rapidly turning wheels of a new buggy.

Some red papers were then attached to the spokes of a mounted bicycle wheel, and when this was turned at a moderate speed the observer could see the red of the papers occasionally. He was not able to see the red on the spokes very often if he merely fixated a point past which the spokes were moving, but if he moved the eyes along with a spoke for a distance of twenty or thirty centimeters and then back with a jerk to the fixation point, he could see the red quite distinctly. He believed that if the wheel was revolved much faster he would be able to see the red on the spokes while the eyes were stationary; but this did not prove to be the case. However, this observation gave rise to another experiment with the perimeter.

The observer was asked to look, not directly into the hole in the gray board of the perimeter, but at a point three centimeters above the center of the hole. As soon as he observed that a paper was placed on the table behind the board, he looked quickly through the hole directly at the colored paper. At other times he moved the eyes quickly to a point about three centimeters to the right or to the left of the hole. Under these conditions the color was seen more distinctly than in the previous experiment with the perimeter.

The same experiments were tried with four similar series of greens for which a slightly bluish peacock and a greenish olive were the contrast colors. The results were similar to those gained with the reds. The only essential difference was that the flashes of green were not quite so intense and were of slightly shorter duration than the red flashes.

The data obtained from this observer have a certain resemblance to some results which can be obtained from normal people. If a disc composed of two differently colored sectors—preferably black and white—is placed on the color wheel and revolved in intense sunlight or artificial light so slowly that there is a pronounced flicker, a variety of colors, "Fechner's colors," can be seen by the normal observer. So far as I have been able to determine some of these transient colors are not found elsewhere in nature by people with normal color vision. Likewise, when red or green was flashed quickly into or flickered in the field of vision of the color-blind observer, he would see and identify the color.

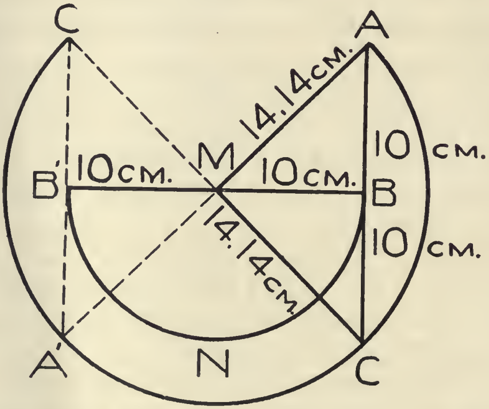
Just as the red-green color-blind person can—under certain conditions of flicker—see the colors to which he is ordinarily blind, so the normal observers, who are ordinarily blind to the "Fechner's colors" can see these under certain conditions of flicker.

B. Mathematics Applied to the Swinging Stick and Experimental Data on Foveally and Peripherally Perceived Motion

A B C is a 20 cm. stick in a vertical position ready to be swung by the stiff metal pieces, M A and M C, through an angle of 180° to the new position C′ B′ A′.

The line B′ M B is 20 cm. in length and is the diameter of a circle of which B′ N B is the semicircle described by the mid-point B of the stick A B C.

Each point on the stick describes a semicircle, and all of these points between B and A or between B and C describe semicircles of different lengths; B describes the smallest one, 31.42 cm., while either A or C describes the largest one, 44.42 cm.; arc A C A′ described by point A is 44.42 cm., and arc C A′ C′ described by point C is 44.42 cm.



Arc ACA′ = 44.42 cm. Arc CA′C′ = 44.42 cm.
Arc BNB′ = 31.42 cm.

The mid-point B, in moving to the new position, describes on the background of the stick a semicircle which is 13 cm. shorter than the semicircle described by either A or C. Both A and C, even though they move through an angle of exactly the same number of degrees as B, move 13 cm. farther over the background than B does. This means that if the observer fixates M while the stick swings to its new position, A and C would seem to move faster and farther than B. This must be the case because A and C stimulate longer streaks on the retina than B does in the same time.

The longer we make M B, or the farther the fixation point is removed from B—and of course from A and C—the more nearly should the amplitudes and velocities of movement of the points A, B, and C seem to be equal.

If, instead of making the distance M B greater, we move M closer to B, the amplitude and velocity of movement of B would seem to decrease relative to the velocity and amplitude of A and C.

Under the condition that M and B are made coincident and M is fixated as usual, the velocity of B would be 0 as the two ends of the stick move around B, both A and B moving in the clockwise direction until they have changed places. Therefore, $B = 0.00$ cm., $A = 31.42$ cm., and $C = 31.42$ cm.

If, instead of fixating B, we fixate A and let C pass through an angle of 180° as usual, we will have the following equations for the relative amounts of motion and velocity of the points A, B, and C: $A = 0.00$ cm.; $B = 31.42$ cm.; $C = 62.84$ cm. If we fixate C instead of A, we will have the following equations: $C = 0.00$ cm.; $B = 31.42$ cm.; $A = 62.84$ cm.

By fixating successively A, B, and C and by permitting the other points of the stick to whirl around the points fixated, we make the velocity and amplitude of movement of the fixated points equal to zero. We will accordingly have the following equations to indicate the greater amplitude and velocity of the peripherally observed points:

Let $B = 0.00$ cm.; $A = 31.42$ cm.; $C = 31.42$ cm.
Let $A = 0.00$ cm.; $B = 31.42$ cm.; $C = 62.84$ cm.
Let $C = 0.00$ cm.; $B = 31.42$ cm.; $A = 62.84$ cm.

These are the results which we get when we neglect the circumstance that the stick as a whole swings through space so that even the point fixated—even though it stimulates only one point on the retina—has a movement of a second and perhaps a third type, namely: that due to its crossing successively objects or points on the background, and that due to the kinaesthetic sensations which arise when the ocular muscles and perhaps other muscles of the body function while the point is coming to its new position. However, owing to the circumstance that during one swing the actual difference between the lengths of the smallest and largest arcs described on the background by the two points B and A or B and C, is only 13 cm., we can (in view of the much larger difference expressed by the above equations) consider that this type of motion is a constant for all points of the swinging stick. Owing to the fact that all other points swing through the same angle while the stick is coming to its new position, the type of perceived motion due to the muscular adjustments made in following the stick with the eyes is constant for all points.

In view of the fact that the peripherally perceived parts of the swinging stick seem to move only slightly faster than the directly fixated portions of it, we are compelled to conclude from the preceding mathematical deductions that, relative to our estimate of motion at the foveal regions, we underestimate the amount of movement at the peripheral regions. The following experiments bear directly on this problem.

Experiment 1

The essential part of the apparatus was a light-proof box which contained an electric light. In the front of the box was a sliding door with a three-millimeter hole which the light rays could shine through. The light could be made red, blue, green, or any other color by merely placing an appropriately colored glass inside the door so that the light rays must pass through the glass before striking the eye of the observer.

The sliding door was drawn back and forth through definite distances while the observer fixated directly a bright spot in the room only a few centimeters from the movable light; this was foveal observation of the light. In order to obtain peripheral observation, the eyes of the observer were directed to a spot about two meters to one side or above the movable light. The visual angle for peripheral observation of the light was about 45°, while this angle for foveal observation was approximately 5°. The observers estimated in centimeters the extent of movement of the light.

Twenty-four of the twenty-seven observers who took part in this experiment, underestimated the extent of movement of the light under all conditions, i.e., at foveal and peripheral fixations. Twenty-two of the twenty-seven underestimated the extent of movement at the periphery more than at the fovea.

Experiment 2

The object and results of this experiment are essentially the same as those of the previous one. The essential differences are: A greater number of people observed, a greater number of tests were made, the apparatus was slightly different, and colored papers were used instead of the colored lights[4].

[4] Owing to the circumstance that in a preliminary experiment (of which the data are not considered in this article), some of the observers possessed illusions of distance of the moving paper that was being observed either foveally or peripherally, special precautions were taken in the present experiment to control this factor. The means resorted to consisted in using papers of four colors: blue, green, orange, and white. Of these blue is decidedly a receding color, orange is an advancing color. The green used was about intermediate between blue and orange, and even though white varies considerably, it should be ranked between orange and green. Owing to these differences, it was presumed that the judgments of the extent of motion of the differently colored papers should vary in predictable ways, but no difference was determined.

Fifty-two observers were tested, but the judgments of two were discarded later. One of these two was entirely blind in one eye, and the other eye was so weak that he could not read his own lessons. The other observer failed to follow the instructions; he failed to record some of his judgments. Each of the other fifty observers made and recorded on the data sheets 36 foveal and 36 peripheral judgments. Accordingly, the number of judgments to consider is 1800 foveal and 1800 peripheral ones. These foveal and peripheral judgments were made alternately by each observer. If the first one was foveal, the second one was peripheral, and so on. The actual magnitudes of movement presented were never the same for two successive stimulations. The following double series of magnitudes, which range from 5 to 16 centimeters inclusive, shows the order in which they were presented in stimulating alternately the fovea and periphery:

Fovea	10	8	14	6	10	8	14	6	10	8
Periphery	14	6	10	8	14	6	10	8	14	6

Fovea	14	6	9	15	11	12	9	15	11	12	9	15	11
Periphery	10	8	11	12	9	15	11	12	9	15	11	12	9

Fovea	12	13	7	16	5	13	7	16	5	13	7	16	5
Periphery	15	16	5	13	7	16	5	13	7	16	5	13	7

The apparatus was an arrangement which permitted controlled movement of a small piece of paper of chosen color through desired distances in the vertical or horizontal direction, while the observer fixated a stationary spot either very close to or at a greater distance on either side, above or below the moving paper. The spots to be observed had, as a background, a large gray cardboard which hid the operator —who stood behind it—entirely from view. The movable parts were attached to fine wires which led back to the operator and which could be seen by the observers only upon very close inspection.

The data gained from this experiment show that the foveal judgments were, on the whole, more accurate than the peripheral ones. Fluctuations above and below the average of the actual magnitudes employed as stimuli occurred in both cases; but the fluctuations above and below the average were much less among the foveal judgments than among the peripheral judgments. It is also the case, as is suggested by the averages that follow, that the fluctuations below the average of the actual magnitudes were greater and more frequent than those above the average. The visual angle for the foveal judgments was ca. 5°, and for the peripheral judgments ca. 30°.

Actual magnitudes in centimeters	5	6	7	8	9	10	11	12	13	14	15	16
Foveal judgments (50 observers)	4.61	5.76	6.53	7.74	8.50	9.30	10.26	11.37	12.22	13.43	14.40	15.22
Peripheral judgments (50 observers)	4.58	5.69	6.33	7.65	8.44	9.31	10.14	11.30	12.00	13.21	14.36	15.11

Average of the actual magnitudes	10.50 cm.
Average of the foveal judgments	9.95 cm.
Average of the peripheral judgments	9.84 cm.

These figures show—as a general inspection of the data shows plainly—that the peripheral judgments are not only less accurate than the foveal ones, but also that the former are more pronounced underestimations. The probable reason, therefore, that the indirectly observed end of the swinging stick does not appear to move more than it seems to, is that with peripheral retinal regions we generally underestimate motion more than with the foveal regions.

General Conclusions

1 If we start with the fovea as the zero point for measurement, the magnitude of a given retinal zone of a normal or color-blind individual ranges from zero to the numerical value which represents the entire retina.

2 For both the normal and the color-blind, the more carefully a colored paper is fixated the sooner it disappears for all regions of the retina.

3 Individuals for whom a given color disappears very soon when fixated either foveally or peripherally, are color-blind in the same sense as the majority of people are color-blind—at the peripheral retina primarily.

4 Motion and distance are perceived less accurately with the peripheral than with the foveal regions of the retina.

5 Motion and distance are underestimated more with the peripheral than with the foveal retina.

6 The so-called "illusion of the swinging stick" is not an illusion in the particular sense that it has been generally assumed to be. On the contrary, it is an illusion in the sense that the indirectly observed end does not appear to move faster or farther at each swing than it seems to.

Theoretical

The explanation which I will now offer for the various phenomena previously discussed are of course of secondary importance to the facts. I will therefore devote as little space as possible to theory.

The fact of the self-induction of colors is of great importance. This fact is: *Every color induces first those colors which are most similar to it and lastly its most dissimilar or antagonistic color.* We can verify this statement in a number of ways. The simplest means, however, consists in fixating *carefully* a point on a colored patch (*e.g.* on a red disc for the Bradley color wheel) that lies on a background of gray, white or black. If we choose a white background it will be noticed within a few seconds—if the disc occupies a considerable portion of the visual field—that the entire background is taking on a reddish hue and that the red disc is becoming white. In short, the background color induces itself over the red and the red induces itself over the background. After a few more seconds of this mutual self-induction of the colors, the white and the red become the same qualitatively. This means that the border line between the original red and the white has disappeared. We are now inclined to say the specific red patch has disappeared; all we see is a light red over the entire field of vision. If we would use black instead of white as a background, we would eventually see an expansive dark red instead of a light red. After much longer fixation, the red disc passes through gray to green. The background, too, eventually takes on a greenish hue.

If the red disc is small relative to other colored surfaces in the field of vision, it will disappear sooner than if it is larger. This observation may be formulated as follows: *The self-inductive capacity of a color varies directly with the stimulus area.* A background color induces itself over a small area of red more readily than over a larger area; and, conversely, a large area of red induces itself over the background color more readily than a small area of red does. We then have an explanation for the circumstance that a small area of red may disappear without making the background noticeably reddish.

If the red is fixated indirectly (*i.e.*, with a peripheral retinal region) it disappears or resembles the background color sooner than when it is fixated foveally. It is easily determined that the farther we go towards the periphery, the sooner the red resembles the background color or seems to disappear entirely. At the extreme peripheral retina, the red may be of such brief duration that we may be able to observe it only when it is flashed upon the retina. We may formulate this fact of observation as follows: *Self-induction of colors at the peripheral regions of the retina is* *greater than at the foveal regions.* The self-induction seems to be, in fact, so rapid at the periphery that we can observe even the sun peripherally without carrying with us any specific colors as after-effects. If the self-induction of colors occurred as rapidly at the foveal as at the peripheral retinal regions, we would be color-blind at the fovea as well as at the periphery. The possibility of our being blind to certain colors and not to others would depend upon the differences in the self-inductive capacities of the various colors. The self-inductive capacities of different colors actually vary. This is determined by observing the rates of disappearance of different colors when fixated by normal individuals. Ordinarily, green disappears a short time before red, both red and green disappear sooner than blue or yellow, and blue and yellow disappear at about the same time. The normal individual is then more nearly blind at the fovea to reds and greens than he is to blues and yellows. If the self-induction of colors in general should occur more rapidly than usual, the individual would be blind to reds and greens at least, and if it would occur still more rapidly, he might be blind to blues and yellows as well.

A histological examination of the retinal elements furnishes us certain facts which might enable us to explain the more rapid color induction at the peripheral parts of the retina. 1. The periphery is better supplied with rods than with cones. 2. The entire cone structure is a neurone composed of a large knot (the end-organ), a cell nucleus, and a fiber with an end-brush. 3. The entire rod structure is a neurone composed of a large knot (the end-organ), a stretch of fiber, a cell nucleus, and then a stretch of fiber (without an end-brush) in which there are a number of little knots distributed. If we call these little knots sensory organs, the rod structure should be more irritable than the cone. We would even expect an animal with rods only to see better in the twilight than an animal possessing cones only. The idea that the rod should be the more irritable type of retinal structures owing to the presence of the little knots, can be arrived at by another form of reasoning. Such little knots are found in the nerve networks in some of the cutaneous end-organs. The end-organ for pain, however, does not possess these; and common observation teaches us that it is considerably more difficult to stimulate the end-organ for pain than it is other cutaneous end-organs. Of special interest, too, is the observation (mine) that such little knots are common in the nervous system of the Japanese dancing mouse. The greater number of these little knots disappear with age, forming a synapse-like figure along the axone. A study of the behavior of this animal shows that it is highly irritable, and that the irritability or susceptibility of the animal to stimuli decreases remarkably with age.

The discussion of the irritability or susceptibility and the self-induction among the rods and cones may be summed up as follows:

$$\frac{\text{susceptibility of rods}}{\text{susceptibility of cones}} = \frac{\text{self-induction among rods}}{\text{self-induction among cones}}$$

This means only that stimulation of a rod with its many sense-organs causes a greater response of the neurone than is caused by stimulating a cone with its single sense-organ, and that the strong response in the rod is more effective as a stimulus for the neighboring retinal structures than is the weaker response within the cone.

In considering the judgments of the extent of motion of objects in the foveal and peripheral portions of the fields of vision, we must again be concerned with the relative extents of self-induction of colors over these areas. If an object moves downward in the field of vision, it leaves a streak of end-organs of the retina responding at least for a short time. This streak that we perceive may be called a positive after-streak or, in cases, a memory image. The first formed end of the streak becomes indefinite and disappears first. If we estimate the extent of movement immediately, the judgment will be more correct; but even then it will be underestimated because the streak begins immediately to grow shorter as it becomes indefinite at the first formed end. Within limits, the longer we wait to make the judgment, the more we underestimate the actual extent of movement of the object. If we stimulate a peripheral region of the retina in the same way, the judgment of the extent of motion will be underestimated to a greater extent than at the fovea, because the induction among the rods is greater than it is among the cones, and the streak grows shorter with a correspondingly greater rapidity. We therefore underestimate the extent of motion more at the periphery than at the fovea.

At this point I wish to express my appreciation to Mr. E. H. Payne, student and assistant in the Department of Experimental Psychology at the University of Missouri, for the aid he gave me in obtaining many of the data presented in the present article. Mr. Payne constructed some of the apparatus used and spent considerable time as operator.

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Editorials

This Journal

THE purpose of this *Journal* was expressed in a few words at the time of its foundation and appeared in the opening pages of the initial issue. We repeat: It is to serve as a carrier of knowledge on important phases of optics as applied to visual problems, to stimulate further development and research along such lines and to correlate and join up those findings in allied fields which may serve it and which may open up new and unexpected avenues of approach. To this end some of the articles in this *Journal* will partake of the character of original research papers, while others will be résumés of important phases of visual optics. The subjects treated and discussed in either manner will be of a varied character in the hope that all readers scientifically interested in problems pertaining to vision and all that this term connotates, as well as topics germane thereto will find something of value and of interest.

Those of us who are interested in the gathering together of the pages which appear in the various issues of this *Journal* have endeavored to carry out this self-appointed commission. The editor is actuated by one motive only in his selections of the materials which are to be parts of this *Journal*, namely: that there be the semblance of truth in that which is discussed and that the presentation of the subject matter clearly indicate, above all else, a *thinking* brain desirous of putting before the reader that which is believed to be of value and a contribution—whether original in character or of the nature of a correlation of facts which are presumably known but which are generally not found so to be—upon a topic germane to the field of physiological optics.

It so happens, therefore, that articles will appear from time to time which do not receive the sanction of the editor to the degree that the arguments or conclusions are accepted. Surely the reader would not throw such an arduous and impossible task upon an editor, made of the same "dust to dust" as are other men, as to demand of him that all that is committed to these pages shall be one-hundred percent acid proof and pure. No, indeed! Personally we read any article, no matter of what character, by whom written or where printed,—and that, too, possibly wholly unconscious of the way in which we are reading it—in order that we may, firstly, gain information and acquire that which is the truth as judged by the logical sequence of premise and conclusion as tested by experience; or, secondly, that we may be more firmly rooted in the faith of which we are possessed, by being made to realize the significance of the points discussed from a new or different angle; or, thirdly, that ultimately we may reject in whole or in part the conclusions of the writer and put our mental fingers upon that which we believe to be in error and thereby be stimulated to renewed thought and further investigation. Surely it is not necessary in these pages to point out how often spurious arguments and erroneous explanations or conclusions have crept into the pages of science, to become ultimately worthless, but which have served as the forerunners of that which has come after—the wonderful unfolding of the simple Truth. Is it not true that all that which is worth while in life and all that which is the Truth is simple? Surely accommodation, convergence, hypermetropia, myopia, astigmatism and so on *ad infinitum* are common, but how much real, simple Truth have we yet to discover with reference to all these? Indeed we shall be most fortunate if these collections of pages carry occasionally within their covers some great but simple Truth.

The Articles in this Issue of the Journal

THE interrelationships between illumination and eye-strain are being appreciated and realized at the present time as never before. It does, indeed, seem strange that illuminating engineers, on the one hand, should know so little about the functionings of the human eye and fail to consider the possibility that many of their conclusions which, from the standpoint of illuminating engineering, may be worthy of acceptance are actually, on many occasions at least, of little value because of the fact that the ocular errors and the reflexes produced by these errors have, to the best of our knowledge, rarely been taken into consideration by them. And again, those who put into practice the art and science of ocular refraction and engage in ministrations to the physiological and anatomical failings of the human eye are often ignorant of the best working conditions, from the standpoint of illumination, for these eyes which they have cared for, and therefore often have their excellent conclusions set at naught by working conditions which are not conducive to ocular comfort and bodily efficiency. The fact that the problems of eye-strain and the problems of illumination often have an important bearing one upon the other is but another illustration of the fact that no one branch of science can be sufficient unto itself, but that all are members one of another. We believe that we are correct when we say that the great problems of science awaiting solution today are border-line in character; in the realm in which we are interested, we must look for solutions from the fields of psychology, physiology, physics and the broad field of medicine—in the true sense of that word—as they are brought into contact with each other. The article by Professor Woll of the Department of Hygiene of the College of the City of New York gives us simple statements from the pen of a man who has made a more than cursory study of the relationships of the physiology and physics of vision and the physics and engineering of illumination. We feel that much along these lines awaits discussion and solution and that there should be much closer coöperation between the engineer who deals in the practical problems of light distribution and the conservators of vision.

We have quite commonly been taught and probably most of us have believed that we cannot detect chromas with the extreme peripheral retina but that we can detect motion much better with such peripheral portions than with the foveal region. Dr. Swindle, Professor of Physiology in the Marquette School of Medicine, presents in his paper on "Perception of Colors and Movements with Foveal and Peripheral Regions of the Retina" experimental data which bring him to conclusions which are directly opposed to both of these statements. For he believes that in general any color which is perceived at the fovea can also be seen at the periphery of the retina, although for a briefer period, and again that motion and distance are followed less accurately with the peripheral than with the foveal regions of the retina. Furthermore it seems probable that motion and distance are underestimated more with the peripheral than with the foveal retina. There is much of value in this article and it should stimulate further investigation and elicit considerable discussion.

There is nothing so helpful to a student—and we should be inwardly proud if we feel that we can really class ourselves as such in each and every case—as a résumé of a year's contributions along any line of scientific endeavor or a logically presented review of the essential and important conclusions. Many of us can look back upon our college days—those days of *training*—and remember with what agony we approached the hours for written reviews and final examinations. Such examinations and tests were probably of little significance to the teacher in the formation of his judgment of what he believed we had gathered from the course he had given, unless perchance he was foolish enough to lecture from day to day and, as a result, do all the work and leave us in ease and comfort to await the "judgment day." To the writer, there was never anything of permanent value gained, or ever to be gained, from preparation for an examination, *per se*, other than this most valuable acquisition, which would possibly never have been gained by any other method, namely:—A joining together of the individual pieces to make a composite structure of beauty and of service. So it has been all through life: you and I read this article and that essay, first here and then there, sometimes in the comfort of the hearth fire and sometimes in the odd moments of a busy day; we seize the facts and evidence presented only to lose sight of them as time passes on. We fail to co-ordinate materials and data; we fail to grasp the significance of one piece of scientific information as related to another because of the fact that we do not impose upon ourselves an "examination" and force ourselves to prepare a review of the literature. We are pleased to present the résumé of important literature appearing during the year 1919, on general visual phenomena, from the pen of Dr. Troland of the Department of Psychology of Harvard, for the reason given above if for no other reason. This article gives us a co-ordination of experimental and theoretical work bearing on vision which we could never possess unless we were willing to do the work which the writer had to do in order to produce his product. And again we are sure that we have missed reading quite a number of the papers which he has cited and we should be quite surprised indeed if you did not find yourself also in that same condition; hence we shall all have something worth while to include in our study hours. We have the expectation of presenting in the next issue of this *Journal* an article on "The Progress in Visual Optics in 1920" by the same writer.

Hyperphoria

ONE of the advantages of frequent conversations with one's colleagues on matters of ocular practices and methods is the inevitable occurrence of some remark which causes the listener to refresh his memory on such topics at a later date or which presents to him evidence that certain tests ought always to be made when particular data exist and thereby directs the attention to possible omissions in his routine of examination. Such an occasion arose recently in our own experience, for in the course of a conversation which we had with a keen and painstaking student of all points relative to ocular refraction he made the statement that he always took the binocular fixation fields in any case showing an apparent vertical imbalance for the reason that he often found paresis and was thereby enabled to properly prescribe a prism instead of dividing the prism between the two eyes or placing it in the opposite direction before the other eye. The facts presented were not new, and yet we are wondering: How many take the binocular fixation fields in every case showing a vertical imbalance? We confess that we have not done so, nor have we in most cases taken the versions by any method which might be considered especially trustworthy. It is, in passing, a question in our own mind as to whether or not it is proper practice to put the whole of the prism prescribed before the paretic eye, but it is obviously improper, so we believe, to place it before the eye the vertical recti of which are not abnormal in their actions. These remarks we hope will induce readers to make a careful study in their own practices as to the advisability of including as a part of the tests in all cases showing a vertical imbalance of one or more degrees the matter of the taking of the binocular fixation fields.

As is well known, hyperphoria is a tendency of one visual line to exist above that of the other. Such a condition is fairly frequent and if it is of low amount it may not interfere with health or with the comfort of the eyes. Hansell and Reber (*Ocular Muscles*) state that 20 percent of several hundred consecutive cases showed a hyperphoria of one-half degree or more. Other data given by Carpenter, Posey, Bannister, Howe and Williams indicate that about "one in ten of all patients who are the subjects of muscular or accommodative asthenopia will during the preliminary examination display some degree of vertical imbalance, either alone or associated with esophoria or exophoria." Certainly the degree of the hyperphoria, *per se*, is of no significance as to the possible reflexes or derangements which may be produced, any more so than is the case with the amount of the astigmia, for instance. Those having small amounts of hyperphoria and who are engaged in close work may have to abandon such work because of very small errors, whereas a person having a larger amount but leading an out-of-door life and possessed of a rugged constitution may carry several degrees of hyperphoria without any apparent discomfort.

To be sure, spurious hyperphoria is to be carefully guarded against, particularly in the matter of decentration of lenses and mal-functions of eyes with reference to test lenses either as used in the trial-frame or in the phoro-optometer. Especially is this true in cases of more than the ordinary corrections: for a 4 D. S. decentered two and one-half millimeters will thereby introduce one prism-dioptry. Likewise, it is possible that the hyperphoria is concomitant with a condition of esophoria, for example, in a case of hyperopia, simple or compound; in which case the relief of the hyperopic condition may remedy the esophoria and also largely, if not wholly, remove the hyperphoria.

The symptoms of hyperphoria cannot be said to be characteristic of this condition only. There may be included, however, the following: (1) Chronic hyperaemia of the lids, (2) epiphora, which is generally unilateral, (3) defective vision, for the hyperphoric eye may not be raised by any lenses to normal, (4) confusion of images, especially when, after monocular tests, the two eyes are allowed to work together, (5) binocular vision may be less than the better monocular vision, (6) the characteristic turning of the head, to avoid the error, and (7) occasional peculiar facial expression, especially the furrows above one eye or the raising of one eyebrow higher than the other. Furthermore, it may be pointed out that symptoms of vertical imbalances include painful eyes, drowsiness from long-continued near work and sensitiveness to light.

The presence or absence of hyperphoria should not be based upon one test alone: in fact, it is never safe to depend solely upon any one method in the practice of any science. There should always be a system of checks. This is especially true in the case of hyperphoria, *i. e.* vertical imbalances.

The commonest method of testing for such imbalances is the use of the Maddox rod, the head being in the primary position. The test light should not be high or low as we so often find it, but as nearly in the primary position as possible. The imbalances indicated should be the same when the Maddox rod is placed before either eye and also when it is turned over: if not there is evidence of a slight paresis of one of the elevators or depressors or again the Maddox rod may be imperfect. Incidentally, every practitioner should take occasion to check his apparatus and find out its degree of perfection. One should always be on his guard against the possibility of the fusion of the streak and light and we believe that two simple check methods exist: Firstly, to use the simple cover test in conjunction with the Maddox rod test, for immediately upon uncovering one eye and getting the answer as to the relative positions of streak and light, the operator is enabled to determine whether the full latency of imbalance has been disclosed. Secondly, to use such an amount of prism, base in, as to produce diplopia and to then determine when the two lights—one of which may be made to appear red through the use of a red disc—are in a horizontal plane. The parallax method when used under proper conditions and surroundings is capable of giving reliable results and of disclosing latencies, and is susceptible of such delicacy of application that, as Duane claims, as low as a quarter degree of hyperphoria may be disclosed.

The question often arises as to whether or not the ametropic corrections should be worn during all tests. If one test only is possible, and all spurious effects from tilting of head, improperly placed lenses and so forth are guarded against, the tests should be made while the corrections are worn. But we feel that tests with and without corrections should be made since, for example, an esophoria accompanied by a hyperphoria may be diminished or removed by the application of lenses correcting the ametropia and through this reduce the hyperphoric condition also. And again, we have found conditions of hyperphoria of small amount to arise with corrections present, when such vertical imbalances did not exist when the naked eyes were tested, due care being exercised to avoid improper testing.

The duction tests at distance, *i. e.* 20 or more feet, as measured by means of prisms base up and down applied until diplopia ensues, should be the next step in the examination, we believe. We thereby obtain the superduction and the infraduction of each eye. Normally these are of the value of two to three prism dioptries. Generally speaking, the superduction and infraduction should be equal. A difference of a degree or more in these ductions on the same eye indicates a probable hyperphoria. If the Maddox rod or other test has indicated a hyperphoria and the duction tests give differences in the prism power of upward and downward fusion, we may feel certain of a condition of hyperphoria. Some one has remarked that a superduction of over 3 degrees is suspicious of hyperphoria, but many will not be willing to accede to this statement.

In cases in which the superduction and infraduction as found by prism tests are equal and yet where hyperphoria is suspected it may be advisable to get the fields of monocular fixation, particularly the upward and downward excursions. In all such tests the head should be rigidly held and the test-object followed by the eye. Hansell and Reber suggest the use of a small card carrying a black dot which is to be carried as far up and as far down the arc of a perimeter as the eye will follow it without wavering or receiving a blurred image of the object. The other eye is to be occluded as in ordinary perimetry. A modification of this test is to use a small electric retinoscopic or ophthalmoscopic lamp, the head of the instrument being removed before use. As a general rule this examination should show at best 35 to 40 degrees of upward and from 50 to 55 degrees of downward excursion. If the upward or downward rotation is insufficient, the deviation is due to weakness or to paresis of one or more of the vertical recti. In this case diplopia can be obtained when the eyes are twenty or more degrees from the primary position. The diplopia will, of course, increase as the test-object is carried in the direction of the weak muscle or muscles.

The binocular fixation fields are readily obtainable and much information of value may be thus often secured by a search of the extreme peripheral portions of these fields. A small electric lamp may be used in an otherwise darkened room, the person under test wearing a red or other colored glass before one eye. A hand perimeter may be used to advantage in these examinations. The existence of binocular single vision in all quadrants or portions of the test light with the arc of the perimeter set at various angles, indicates that there is no paresis of any of the elevating or depressing muscles. Should there be a lateral diplopia and the two lights remain in the same relative positions with reference to a horizontal plane in all quadrants of the test, the examiner is then assured of the fact that no vertical imbalances are associated with the lateral condition and that there is no paresis of the vertical recti. Without the use of a perimetric arc the binocular fixation fields should be tested in nine positions: three in the plane of the primary fixation, including straight away fixation and to the right and to the left thereof; three similar tests in such positions as to involve the elevators and again three tests involving the depressors. In this manner hyperphoria and hypophoria may be differentiated. For instance, in a case showing a few degrees of left hyperphoria or right hypophoria at both distant and near points, it is possible that a search for diplopia in the extreme peripheral portions of the binocular fixation fields will show vertical diplopia with the right image *higher* in the middle and right upper fields, being most marked in the right upper field. According to the laws of projection, therefore, there is evidence that there is a paresis of the right superior rectus. Hence this condition of *left hyperphoria* is properly diagnosed as one of *paretic right hypophoria.*

Simple tests for vertical imbalance at the ordinary reading points include the Graefe's dot and line test with the use of the Maddox double prism or the small electric lamp and the Maddox rod test when used in conjunction with the cover test.

The Progress of Visual Science in 1919*

A Review and Summary of the Literature

Leonard Thompson Troland, Ph. D.

Visual Disorders due to War Injuries

NOT the least of the contributions to scientific knowledge due to the war is to be found in the firm establishment of Henschen's theory of the point for point representation of the retina upon the calcarine cortex. A very comprehensive article by Best (13) summarizes the results of studies upon disorders of the visual function due to war injuries of the central optical apparatus. He first contests Igersheimer's doctrine that all injuries to the optic nerve tend to produce scotomas centering about the blind spot, and then reviews the evidence for the specific localization of various visual functions in the cortex. The calcarine fissure is the center of relative binocular localization, being responsible for the establishment of visual direction and the combination of disparate sensations. All the evidence is in favor of a point to point representation of the retina in this region, and hence is contrary to von Monakow's idea of a diffuse distribution of the optic connections. Psychologically higher visual functions, such as motion perception, contrast processes, visual recognition, perception and imagination, and certain aspects of color sensibility are dependent upon centers physiologically higher than the calcarine region. Destruction of this latter region has no more serious an effect upon the general visual consciousness than has destruction

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*A considerable portion of the material given in this article was used by Dr. Troland in an article which appeared under the title "Vision—General Phenomena" in the *Psychological Bulletin*, vol. 17, pages 201-228, 1920. We are pleased to acknowledge our indebtedness to the publishers of the *Bulletin* for their permission to use any such materials. The present article is to be considered in conjunction with the article which follows in the next issue of this *Journal*. ED.

of the retina or optic nerve. A careful study of this paper is recommended to anyone interested in a thorough analysis of the dependency of various visual functions upon the brain processes. Morax, Moreau, and Castelain (73) report results of a study of visual defects in 86 cases of wounds in the occipital region of the cortex, dividing these cases into seven characteristic groups. Among these cases there was only one in which complete blindness was caused by an occipital lesion, vision always tending to remain in the fovea except where both cerebral hemispheres were seriously damaged. Morax (72) continues with a theoretical discussion of the cerebral localization of macular vision, on the basis of the data accumulated by himself and his collaborators. He finds that the cortical center for macular vision is distinct from that of peripheral vision although contiguous with the latter, lying posterior to it in the calcarine fissure. The macula is divided into two halves, each of which is represented on one hemisphere only. The entire *fovea*, however, has a representation on both hemispheres, the centers for the fovea lying posterior to those for general macular vision on the edges of the calcarine fissure. Monbrun (71) summarizes results of studies upon war injuries to the visual cortex which confirm those of the investigators above considered. He finds the visual projection area to be limited to the lower portion of the cuneus and the upper portion of the lingual lobe within the calcarine fissure and strongly supports Henschen's theory of point to point retinal representation. A partial destruction of the cortex in this region produces a scotoma with definite limits within which there is absolutely no vision. Like Morax he finds the macula to be projected on the posterior surfaces and the periphery of the retina on the anterior ones. However, there are wide individual differences in the cortical representation of the macula. Although the perceptions of light, form and color may be differently affected in different stages of hemianopia the projection of these three functions upon the calcarine cortex appears to be identical. The probable paths of the optic fibers from retina to cortex are discussed in some detail. Wilson (99) reports 5 cases of local scotomas determined by wounds in different portions of the occipital lobe which present evidence in favor of Holmes' view that the vertical axes of the visual field are represented in dorsal and ventral margins of the visual projection areas.

De Schweinitz (87) analyzes the visual disorders resulting from war psychoneuroses. General loss of visual power and enfeebling of color vision often occur, as well as disturbances of the motor functions of the eye. There may be a reduction of acuity, cloudiness of vision, or constriction of the visual field, but in practically every case the symptoms are characteristic of a psychological situation rather than of an anatomical injury and the patient usually behaves in such a manner as to avoid bodily injury although his visual consciousness is seriously curtailed. Disorders of this sort would appear to be determined by affections of visual processes in the association areas of the cortex rather than in the primary occipital region. Hoeve (52) contests Igerscheimer's view already referred to above regarding the results of injuries to the optic nerves or tracts. The arrangement of the fibers in the optic nerve is such that injuries to the latter should be expected to produce scotomas having a position in either the monocular or binocular visual fields roughly corresponding with the positions of the lesions in the nerve cross-section. Well known types of scotomas due to optic nerve injuries do not center in sector form about the blind spot, as claimed by Igerscheimer, whose views are neither theoretically nor clinically defensible. Spaulding (91) describes two interesting instances of scintillating scotoma, observed upon himself, which seem to be associated with abnormalities in refraction.

Oculomotor Functions

A considerable number of studies of the motor and refractive functions of the eye are reported. Stefanini (92) discusses the movements of the eyes in response to sounds produced on opposite sides of the head. He finds a reflex tendency of the eyes to follow the sound, even when the displacement of the latter is subjective and due to binaural beats. Lamb (64) notes that the only practical application of the mathematical "theory of finite rotations" is to the movements of the eye-ball. He presents a new mathematical analysis of these movements which is simpler in form than that of Helmholtz, with which it is critically compared. He concludes that "the cardinal advantage of the fact that the eye conforms to Listing's law * * * consists in this, that the test of superposition is fulfilled for straight lines which pass through the center of the field of view, in the primary position." Liddell (65) examines experimentally the validity of Ferree and Rand's theory that so-called fluctuations of visual attention are due to eye-movements. Photographic records of the eye-movements of seven subjects were secured during such fluctuations, and no correlation was found between the movements and the phases of visibility and invisibility of minimal visual stimuli. The results are deemed to refute the views of Ferree and Rand, which were based upon less adequate data.

Pupillomotor Function

Weve (97) contests Behr's theory that stimulation of the nasal half of one retina tends to cause a *direct* pupillary reaction only, while stimulation of the temporal half tends more towards a *consensual* response. Observations upon twelve subjects show clearly that direct and consensual reactions are brought out to the same extent from both retinal regions. The literature dealing with the pupillomotor function is reviewed and various possible arrangements of the pupillomotor paths in the optic tract are outlined. Abelsdorff (1) describes a case of war injury to the optic nerve, resulting in a peripheral but no central scotoma, in which the pupillary response was destroyed. Since central vision was intact, he argues for the existence of special pupillomotor fibers, distinct from those responsible for sensation. Engelking (30) has determined the minimal brightness necessary to produce a noticeable pupillary reaction, using both photographic and entoptic methods of observation. After twenty minutes dark adaptation the first intimation of response appeared at an illumination of 0.001 meter candles, but a positive reaction was not obtained until 0.025 - 0.04 meter candles were reached. The latter value corresponds with the absolute threshold of cone vision. Engelking concludes that a slight, faltering, pupillary response is aroused by stimulation of the retinal rods, but that the function rests mainly upon the cones. A large stimulus field, 23.0 by 16.3 degrees, was employed. French (38) reviews the physiology of the eye, and then presents new data concerning the relation between pupillary area and the intensity of the stimulus. He finds the equation, $A = kI^{1/5}$ to hold for these two factors, k being a constant.

Refraction and Ocular Media

Hartridge (45) endeavors to explain the fact that the focal length of the crystalline lens is noticeably shorter than what would be expected from its form and refractive index, by pointing out that the increasing optical density of the lens towards its axis will bend the wave-front of the light by differential retardation, as it moves through the lens substance, this effect being added to the refraction which occurs at the surfaces. The same investigator (44) discusses aberrations of the ocular refractive system which affect peripheral vision. The curvature of the retina is found to compensate quite perfectly, up to 30 degrees (at least in the rabbit's eye), for that of the field of the lens, the size of an image being practically independent of angle, a necessity for stereoscopic vision. Lockwood (66) finds that with a pupil larger than four millimeters in diameter the spherical aberration of the eye appreciably influences distinctness of vision, and with a fully dilated pupil the difference in refracting power between the central and edge zones amounts to 6.6 diopters.

Bailliart and Magilot (6) outline a method for determining the blood pressure in the vessels of the retina, and find this ordinarily to lie between 15 and 30 millimeters of mercury. Osborne (75) has examined the aqueous humor of the ox's eye and finds it to be practically free from protein, although otherwise resembling blood serum in constitution. This freedom from protein increases transparency, but can only be explained on the assumption that the containing membranes are waterproof or are in a state of oedema. Descemet's membrane is probably waterproof, but the iris is not, and so the aqueous humor must penetrate the latter with a pressure of about 10 millimeters of mercury. Nordensson (74) finds that the transparency of the anterior boundary of the vitreous humor decreases progressively with the age of the subject, being practically constant for all individuals of the same age.

Diffraction

Sheard (89) and Raman (80) discuss, independently, the causes of the scattered light phenomena seen about small luminous areas in the dark; and arrive at strikingly similar conclusions. Raman first questions Helmholtz's view that these are mainly due to diffraction at the edge of the pupil, and shows by means of a square artificial pupil that the pupil effect, although present, is relatively small, the principal phenomena being independent of the pupil. The halos which are observed strikingly resemble those caused by the diffraction of light passing through a layer of irregularly placed small particles, such as lycopodium powder. In harmony with this interpretation, the use of monochromatic instead of white light brings about marked changes in the phenomena produced by the eye. The two halos which are visible indicate the operation of two sets of particles, of average diameters, 13μ and 7μ, respectively. Sheard's findings are in general agreement with the above: the first colored halo is attributable to the cells in epithelium of Descemet's membrane, the red component of this halo having an angular diameter of 3° 40′; the second halo, which is much fainter, has a diameter of 8° and is probably due to the epithelial cells of the cornea. The sizes of the particles theoretically required to produce the observed effects are calculated to be 10μ and 25μ, respectively, and these sizes agree approximately with those of the epithelial cells.

Ocular Hygiene and Efficiency

In the field of *ocular hygiene*, Hartridge (42) finds the cause of eye-strain to be the attempt to dissociate the reflexes of accommodation and convergence. Eye-strain cannot be due to too great exertion of the accommodative mechanism alone, since it is as common in conjunction with myopia as with hypermetropia. Experiments, with accommodation accomplished by a spectacle lens but convergence still required, produce eye-strain—and to an extent proportional to the success with which the diplopia is overcome. Coblentz (21) presents the spectral transmission curves of various glasses designed to protect the eyes from injurious radiations, such as the ultra-violet and infra-red. Ferree and Rand (35) follow out previous investigations on the power of the eye to sustain clear and comfortable seeing with different illuminants. In the present paper they study the influence of various proportions of ceria and thoria in gas mantles, and find that in general the efficiency of the eye increases with increase in the percent. of ceria. 3 percent. of ceria, however, is somewhat better than 5 percent., which was the highest amount tested. Mantles lacking in ceria produce a greener light than those containing it in some quantity. The results of the tests are presented in numerical and graphical form.

Ferree and Rand (34) also report measurements of the time required to change the adjustment of the eyes for clear seeing at a near point to one six meters away, and *vice versa.* Only the motor factors in the process are dealt with, since other work by the same authors shows that the lag of the sensory changes is relatively very small. For 18 normal observers, the times for passing from the near to far points varied from 0.50 to 1.16 seconds, and for the reverse adjustment between 0.39 and 0.82 seconds, 15 of the observers requiring more time for the first change. The modal time for the double excursion lies between 1.35 and 1.65 seconds. Two types of apparatus were employed and the results are tabulated in full. A small amount of astigmatism has a marked effect upon the efficiency of this function. Forsythe (37) has determined the minimal speed for telegraphic light signaling, as limited by the inertia of the eye. The best ratio for dot: dash: space is 1:4:3. At a distance of 2,700 yards, the minimal time for a four part signal is about 1.6 seconds, both in daylight and at night, although some observers do slightly better in daylight. A gas-filled ribbon filament tungsten lamp, turned on and off electrically, is as effective for such signaling as a shutter. Prantl (78) has studied the speed of reading, with the type at various angles to the ocular horizontal. His graph of the time required with respect to the angle shows two maxima, at 150 and 210 degrees, respectively, in these positions four times the normal time being demanded. At 180 degrees (with the type up-side-down) only 3.7 times the normal is needed. The various factors involved in reading speed are discussed.

Griffiths and Baumgartner (41) have investigated the relation between power to visualize, as tested by the ability to make geometrical constructions mentally, and fineness of brightness discrimination as determined by ability accurately to set a photometer, hoping to throw some light upon the basis of individual differences in image type. Data from 75 subjects, however, show only a very low correlation between the two traits, not enough to warrant the supposition of a causal linkage. There is no correlation at all between memory for letters, and digits, or speed of multiplication, and brightness discrimination.

Optical Illusions

Wingender (100) describes experiments upon many classical geometrical optical illusions by an interesting method. The main lines of the figures were shown by reflected light, while the supplementary lines—inducing the illusion—were added at will by transmitted light. When this addition was made a motion of the main lines, such as to generate the illusion, could usually be seen. A rapid alternation of these two phases of the figures shows that there is a minimal period, about one fourth of a second, required for the illusion to develop; and this time is shown to be the same as that needed for the change from a monocularly conditioned to a binocular stereoscopic perception. It is clearly much greater than that needed for a purely sensory arousal. The general and special conditions for the generation of many well-known illusions, such as those of Müller-Lyer, Zöllner, Hering, etc., are carefully considered: sharp analysis of the figure, and complexity too great to be appreciated as a whole are detrimental to the illusory effects, and the position of the fixation point is of importance.

Henning (50) discusses at great length the reasons why the sun and moon appear larger at the horizon than at the zenith. Observations made by sixty observers in the open indicate that the principal cause of the apparent magnification lies in the red color assumed by the celestial orbs in rising or setting. Not only the sun, moon or stars, but all objects on the horizon which fall within the zone of the reddish glow are subject to the magnification, and the increase in the clearness of details is sometimes as great as would result from use of a powerful telescope. The illusion is reduced or destroyed by observing through red-absorbing glasses. The mechanism of the effect is as follows. The preponderance of red rays, on account of their relatively slight absorption by smoke or vapor, reduces the "atmosphere" of the scene, thus making it appear stereoscopically nearer and sharping its details. The principles involved in the Aubert-Förster and Köster phenomena demonstrate a linkage between acuity, apparent size and apparent brightness, such that increased acuity carries with it increased apparent size but decreased apparent brightness. The celestial magnification effects are instances of these phenomena; the augmented size of the sun and moon at the horizon is found to entail a diminished luminosity. Neither the size nor the luminosity changes are physical. Other principles which may be involved in the illusion are considered in detail, together with the basis of allied appearances, such as distortions of the sun or moon at the horizon, the apparent shape of the arch of the heavens, etc.

Entoptic Phenomena

Wassenaar (94) finds that the vessels of the retina can be seen entoptically projected upon a rotating black and white disk, the color of the entoptic images varying with the speed of the rotation. It is sometimes purplish red and sometimes green. Streaming movements, attributed to the vessels of the choroid, can be observed by a similar method. The same investigator(95)discusses the colors which are generated by alternately covering and uncovering the closed eye.

Bard (9) is not satisfied with explanations which have been advanced hitherto for the invisibility of the blind-spot. He notes that at the *punctum caecum* the layers of the retina do not stop suddenly but with undulations, and that corresponding distortions are observable in objects in the vicinity of the blind-spot. The undulations of opposite sides are supposed to be dovetailed in their projection upon the cortex or visual field.

Visual Space and Motion Perception

The same writer (Bard) discusses anew the mechanism of localization in visual space, finding the simple "geometrical" theory of private line conduction from the retina to the cortex to be inadequate because of poverty of conductors and lack of specificity in the functioning of individual conductors. He believes that each retinal receptor possesses mechanisms which are analytic for direction or position and which impress upon the optic nerve currents, characteristics utilized by the cortex in sorting the impulses spatially. This view is discussed in comparison with classical "local sign" doctrines. In another paper (8) Bard considers the same general problems not only for vision but for audition and touch. Depth perception is not mainly a binocular function, as usually supposed, but depends upon the fact that the monocular retinal image has a thickness, positions within which are sensed by a mechanism which is "natural and immediate."

Eaton (28) analyzes the various monocular criteria of depth, and contends that since monocular vision gives the impression of solidity, it should be called stereoscopic. He finds that the fusion of disparate images is not essential to stereoscopic vision and that its deliverances are even capable of being overcome and reversed by other, and monocular, factors; as in the case of interchanged stereoscopic photographs of familiar objects. In securing a stereoscopic effect, monocularly, from a single photograph it is important that the perspectives of the eye and camera should coincide. The decrease of the sharpness of images with increasing distance is an important factor, as shown by the difficulty often experienced in correctly fusing stereoscopic X-ray photographs where this relationship is reversed. Previous experience is the most important of all determining influences. In general the combined power of so-called secondary criteria of depth (perspective vision) is greater than that of the "primary" binocular mechanism. In a second paper

Eaton (29) analyzes some of these factors in greater detail. He adduces evidence to show that very seldom does our perception utilize simultaneously all parts of both retinal images, and that the determination of corresponding points is not hereditary but is fixed by experience. The principles involved in the fitting together of the two retinal images are discussed in considerable detail, and the functions attached to the separate eyes are found to remain independent until the very highest levels of synthesis are reached. Luster, binocular or monocular, is due to the presence of light in addition to that required for the adequate perception of an object by itself. Other suggestions, of interest to the close student of binocular functions, are offered. Barrie (10) disagrees with Eaton as to the effects obtained by various rearrangements of ordinary stereoscopic photographs, finding the binocular factor to be more powerful.

Kaila (61), in a lengthy article, endeavors to build up an empiristic theory of depth perception in which the disparation of binocular images acts as a "reproduction motive" entering into an association complex based upon experience and containing the final stereoscopic impression. Hering's theory, involving the automatic fusion of two genetically determined depth sensations, is found to be inconsistent with the fact that equal amounts of diplopia may arouse quite different depth impressions if other factors in the general sensory constellation are permitted to vary. In the developed perception the diplopia is of course subconscious, but this does not prevent it from acting as an associative unit. The problem of the cerebral mechanism of this association is considered in some detail, together with the question as to the manner of co-representation in the cortex of corresponding retinal points. The position of the binocular fixation or convergence point, recorded by oculomotor impulses, must also enter into this associative system as a parameter. The theories of the Panum and of the Hering depth phenomena are considered very carefully, and there is an appendix containing a long critique of

Jaensch's doctrine of space perception. Cohen (24) describes an apparatus designed to test stereoscopic vision at considerable distances (30 to 40 feet from the subject). It consists of a dark box displaying an arrangement of four colored letters at different distances, the observer being required to state their order.

A number of papers deal with practical tests of vision designed for the *selection of aviators* or other military recruits. Cantonnet (16, 18) lists seven visual requirements which the aviator should meet and describes tests for each of the visual functions involved. Novel tests for "quickness of acuity" and sensitivity to dazzling are outlined. Methods of testing night acuity and dark adaptation are also presented. The same author (17) describes a binocular vision test designed to measure any deviations from normal of the convergence of the eyes with fixation of objects at various distances. Howard (54) discusses the various factors involved in the visual judgment of distance. An apparatus is described which tests individual sensitivity to change in "binocular parallax" and in the size of the retinal image. Results are given for 106 subjects, 75 of whom were aviators. Binocular parallax is found to be twenty times more important than the size of the retinal image in judging distances under conditions which were used. The normal threshold for the detection of binocular parallax is 8.0″, but 14 observers had an average threshold as low as 1.89″. The reaction time for monocular judgments is much higher than for binocular ones, which latter are practically instantaneous. There is very little correlation between the parallax threshold and visual acuity. Spearman (90) and others discuss briefly various visual factors involved in the efficiency of the aviator.

Kuile (63) offers a mathematical analysis of the apparent motion generated by the binocular fusion of two synchronous, simple, harmonic motions independently presented to the two eyes. The motions occur symmetrically, parallel to a line joining the nodal points of the eyes. The stereoscopically generated motion has an elliptical, circular or hyperbolic path, according to the exact conditions selected. The relative velocities of the apparent motion at various points are calculated and a chart providing an empirical verification of the results is given. Koffka (62) also applies mathematical methods to problems of motion perception. Beginning with Korte's empirically established laws which express the relations between intensity distance and time interval for the optimal motion impression in stroboscopic vision, he uses Wertheimer's theory of the neural "short-circuit" to develop equations for the brain process underlying such vision. The argument is very elaborate, and leads not only to a theoretical analysis of the brain mechanism but also to definite predictions regarding stroboscopic phenomena, which are compared with empirical findings.

Roelofs and Zeeman (84) have made an experimental study of factors controlling the periods during which disparate contours, in retinal rivalry, are visible. Conflicting vertical and horizontal, and other more complex contours were used. Greater acuity of one eye as compared with the other, greater contrast with the background, greater intensity, and eye-movement parallel to the given contour tend to cause predominance. Rivalry is interpreted as a phenomenon of passive attention. The conflict is one of configurations, as such, and not of eye-fields.

Bell (12) reports measurements on the visibility of bright lines and spots. Previous investigators disagree widely as to the smallest angular size of the single spot or line which is visible. In the case of a bright object on a dark background the threshold appears to depend only on intensity, stimuli subtending angles as small as 0.2″ often being visible. The present investigator made tests with German silver wire against a dark background and found the minimal angles to vary from 2.3″ to 0.46″, depending on the nature of the reflection from the wire and that of the background. White thread against a background of black paper was distinctly visible in sunlight at 0.92″, the lowest angle at which any portion could be distinguished being 0.46″. The brightness contrast in this case was 16 to 1. This was less than 1/50 the minimal angle for a single spot under similar contrast conditions.

Camouflage

Luckiesh (69) offers a general outline of the conditions for successful terrestrial, marine and aerial *camouflage*, in which he utilizes the principles of the psychology and physiology of vision. In a second more lengthy paper (68) he discusses the problem of the visibility of aeroplanes. This profusely illustrated article carefully analyzes the problem on the basis of physiological and physical optical principles, and many actual measurements made from aeroplanes of the brightness and other visual values of various types of terrestrial surfaces, and also of sky and clouds. Jones (60) attacks the problem of camouflage in its application to the protection of vessels against submarines, considering in particular the "low visibility phase of protective coloration." He analyzes theoretically the various factors involved and develops a formula for expressing the visibility of an object in terms of the brightness of its background and of the veiling glare necessary to just make the object invisible. An instrument is described which measures visibility in accordance with this principle, which was used in elaborate experimental tests made with model ships variously camouflaged. Photographs of the experimental "theater" employed in this work are published in another place (*Trans. of the Illum. Eng. Soc.*, 1919, 14, 232-233). Results of these measurements are reported in detail and their analysis shows that broken colored systems the elements of which can be perceived increase visibility, while if they are too small to be seen they have no effect. Visibility depends entirely on the average hue, saturation, and brightness values of the object in contrast with its background. The best values of these several factors for characteristic weather conditions are specified. Gibson, Tyndall, and McNicholas (40) present graphs of the spectral transmissions of various filters which were used during the war to detect camouflage or to improve visibility.

Photometry and Visibility

In the field of photometry Ives (58) offers a specification of a standard photometric scale analogous to the thermometric scale employed in pyrometry. The various factors involved are (1) conditions of observation: a field brightness of 2.5 millilamberts, field size of 2°, and the flicker photometer, (2) the method of choosing observers based upon specified test filters, (3) the visibility curve, (4) the mechanical equivalent of light: 0.00156 watts per lumen, (5) standards of luminous intensity, and (6) standards of color. The specification of all of these factors is based upon the most recent data of the author and other investigators. Blondel (14) describes a system of physical photometry similar to that previously reported by Ives. He employs a spectroscope with a template, representing the visibility curve, in the plane of one of the slits and a thermopile to measure the intensity of the combined rays. He describes this arrangement as the "inverse" of that used by Ives.

Hyde, Forsythe and Cady (55, 57) find that Coblentz's energy distribution curve for the acetylene flame is such that a color match between it and a black body could not be made with an accuracy greater than 7 to 8 percent. Measurements made by the present investigators and others, however, show that a close color match is actually obtainable, the corresponding black body temperature being 2360° K. Coblentz (22, 23) defends his work on this subject by pointing out that only very low precision of measurement is obtainable in the blue and violet end of the spectrum but that elsewhere his data correspond well with the above mentioned black body temperature. He offers a table of revised values. The importance of this question lies in the fact that practically all measurements of the visibility curve have been made with the acetylene flame.

Hyde, Forsythe and Cady (56) present a new experimental determination of the brightnesses of a black body at temperatures between 1700 and 2600° K. The empirically obtained values agree well with those computed from the visibility data previously published by the same investigators and based upon direct comparison rather than flicker photometry. The same data also provide the basis for a new estimation of the mechanical equivalent of light as 0.00150 watts per lumen. The value of 70 candles per sq. cm., or the brightness of a black body at 2077° K. (color match with a 4 w.p.c. standard carbon lamp), is proposed as an absolute standard of light.

Adaptation and Twilight Vision

Cobb (19, 20) reports quantitative studies of the process of dark adaptation with special reference to the problems of night flying. An apparatus was designed which permitted a determination of the absolute luminosity threshold at various times in the course of dark adaptation. After the subject had become completely dark adapted his eyes were dazzled for five minutes and later for fifteen seconds and the courses of the adaptation after each of these exposures were studied. The absolute peripheral threshold at equilibrium dark adaptation was found to vary from 1.34 to 9.95 millionths of a candle per sq. cm., the mean value for 15 subjects being 4.97. The recovery of dark adaptation after the fifteen seconds exposure was three times as fast as after the five-minute exposure. There was little correlation between rate of adaptation and the final level attained, and no correlation was found between power to discriminate brightnesses and any adaptation factor. A statistical subdivision and classification of the individual results is presented. Plateaus in the adaptation curves suggest the existence of two factors in the process.

Downey (27) describes a new adaptometer and photometer which utilizes a luminous radium compound as a standard comparison stimulus. The device permits a systematic investigation of the course of dark adaptation, the proper procedure for which is outlined. Tests with this instrument lead to the following conclusions. Dark adaptation of one eye has no effect upon the other, although under similar conditions the rate of adaptation is the same for both eyes. There is no binocular summation of brightnesses in dark adaptation. Recovery from such adaptation is complete in about thirty seconds, after which the same time is required to reproduce the original adaptation as in the beginning, provided bright daylight is employed all over the retina, although when only a small field is used to reduce the adaptation to the daylight level recovery occurs in about a minute. There is a marked dark adaptation in the macula, and even in the rod-free area of the retina. Dark adaptation has relatively little effect upon the threshold for extremely small stimulus fields.

Putter (79) continues the development of his general, mathematically formulated, theory of stimulation. In the present contribution he applies the principles previously deduced to the temporal relations of excitation in the human eye. The laws of fatigue or "*Umstimmung*," and of the growth and decay of visual sensation are derived theoretically and compared with empirical findings. Equations, tables and graphs are given showing the temporal course and limits of the fatigue process, the data of von Kries and Schjelderup being employed in combination with the theoretical relationships. A similar treatment of the facts relating to the growth or "Anklingen" of the sensation is based upon the results of Exner and of Martius. A further contribution, the final one of the series, deals with stimulation processes in general, but some particular visual phenomena are considered. These articles seem worthy of a more detailed study than the reviewer has yet been able to give them.

Filehne (36) discusses certain phenomena which are most readily observed under conditions of twilight vision. Among these are the vibrations of the atmosphere due to temperature differences and movements of thin clouds of vapor such as result from evaporation. Observations upon these phenomena indicate that the rate of decrease of the sensibility of the retinal rods within a circular central field, 2 to 5 degrees in diameter, with increasing brightness of the retinal image is greater than in the remainder of the retina. Experiments on the appearance of a sphere illuminated so as to exhibit a bright crescent and subtending a visual angle of about 3 degrees show that the crescent may cause the general illumination of the sphere to disappear, this being due to the reduced sensibility of the retina in the region concerned. This observation is applied to the appearance of the planet Venus, on which general faint illumination in the crescent stage cannot be seen against a completely dark sky but only in twilight.

Roelofs and Zeeman (85) discuss a possible interpretation of certain cases of night blindness. They estimate the intensity of starlight illumination at 0.0003 meter candles. The visual acuity at this and higher intensities was determined, a relatively slow increase of acuity with respect to illumination being found. Since refractive errors in the eye increase the intensity required for a given acuity the illumination obtainable at night may for individuals with high refractive errors be insufficient to permit adequate seeing, especially with the large pupil which goes with night vision.

Persistence of Vision

Allen (2) reports extremely interesting results of a continuation of his earlier studies on the effect of differential color fatigue upon critical flicker frequencies. His findings "appear absolutely to determine the number of fundamental color sensations." The eye was first fatigued for three minutes with a selected monochromatic radiation, after which—in separate experiments—the critical flicker frequencies for this and other spectral wave-lengths were determined so that curves representing the spectral distribution of these frequencies after fatigue by different monochromatic stimuli could be plotted. In general fatigue lowers the critical frequency, but not equally for all colors, and certain fatiguing stimuli produce no effect upon the spectral curve. There are four points in the spectrum yielding such stimuli, lying at 660, 570, 470 and 420$\mu\mu$ respectively. The effect of fatigue by stimuli lying between these points in the spectrum may be either to decrease the critical flicker frequency in a single spectral region or in two such regions, as the case may be. For example, fatigue with yellow, 577 to 651$\mu\mu$, causes a decrease in the frequency for red and also for green but little decrease for this yellow itself. The spectral regions from which fatiguing stimuli produce no effect upon the frequency curve are regarded as fundamental transition points, and a comparison of these regions with the color sensation curves of Abney, and König and Dieterici reveals a close correspondence with the ends or intersections of the component color curves in question. Fatiguing stimuli which produce only one depression in the frequency curve are regarded as mono-sensational. Data from color-blind eyes corroborate these interpretations and substantiate the three-color theory with its implication that yellow is a compound sensation.

In a second article (3) Allen presents new data bearing on the relation between critical flicker frequency and stimulus intensity. Spectral stimuli were employed, and the results confirm those of Haycraft, who found the critical frequency to be proportional to the logarithm of the brightness, with a shift in the constants of the equation at intensities corresponding with the threshold of cone vision. The relation of the results to the Purkinje effect is carefully considered. Piéron (76) discusses the law relating stimulus intensity, i, with the time, t, required to reach the maximal sensory intensity. The law of Bloch, $i\ t = constant$, holds only for short times. That of Hoorweg-Weiss, first applied to the electrical excitation of the nerve but rediscovered by Blondel and Rey for visual sensation, is much more satisfactory and has the form $t = a\ (i - b)$, a and b being constants, the interpretations of which are considered. Another fairly successful relationship is $t = a/i^n$, n having different values for different departments of sensation. The law of Hoorweg-Weiss is found to hold to within about 2 percent. for eight different kinds of sensory stimulation as well as for several objectively measured nerve processes. Woog (101, 102) reports experiments on the persistence of vision in different regions of the retina. He finds an increase in flicker towards the periphery, using a frequency of 15 to 25 per second, persistence therefore being greatest in the center of vision. His stimulus fields when gradually brought nearer to the eye began to flicker when they subtended an angle of about 9°. In answer to an objection that the greater sensitivity of the periphery to flicker may depend upon the exact level of intensity which was used, Woog states that the interposition of dark glasses between the eye and stimulus surface does not alter the relationship.

Color Vision

Ferree and Rand (32, 33) present new measurements of the chromatic thresholds of sensation from the center to the periphery of the retina and discuss the bearing of their results upon color theories. Supporters of the Hering theory have claimed that the sensitivities to red and green fall off in a constant ratio towards the periphery, the same being true for blue and yellow. The results of the present investigation do not confirm this view. Spectral red, yellow, green and blue stimuli were employed and the chromatic thresholds were measured in energy units at approximately twenty-five different visual angles, ranging from 0 to 92° in the temporal and nasal meridians. The observers had normal color vision and a neutral outlying field equal in brightness to the test field was employed. The results as tabulated and plotted reveal marked irregularities in the increases of the thresholds in passing from the center towards the periphery. There are regions of low yellow sensitivity where there is no correspondingly low blue sensitivity, and the same is true for red and green. In their theoretical discussion (33) Ferree and Rand criticise previous investigators for employing stimuli equated in "canceling power" and determining the points at which the chromatic effects of these stimuli disappear, instead of measuring the sensitivities and chromatic sensitibilities for spectral stimuli at all points. Antagonistic colors may seem to vanish at the same point when in reality there is a wide discrepancy between their thresholds, since a change in position of 2 or 3 degrees may cause a very large alteration in liminal value. They believe it to be impossible to find a red and green which do not vary in quality in passing from the center to the periphery, but it is not an essential of such a color theory as Hering's that such stable stimuli should exist. Although the ratios between the thresholds of antagonistic stimuli vary widely with position on the retina their "canceling powers" remain constant.

Gibson (39) discusses further the similarity between color comparisons made by a normal subject in a "minus red" light and those made by the dichromatic color-blind in ordinary illumination. Because certain dyes employed to color wools are fluorescent it is necessary to place the "minus red" filter between the wools and the eye to produce exactly similar confusions. Cowdrick and Winfield (25) have determined the best conditions for the use of the Hering color-blindness apparatus, which were never specified by its inventor. They find that when artificial daylight is employed at a constant intensity it permits a reliable diagnosis of different types of color-blindness. Rich (81) finds that the commercial "daylight" lamp (Mazda C2) departs too much from actual daylight to warrant its use in establishing color-matches for careful research purposes, although it suffices for demonstration of the laws of color-mixture in laboratory courses. The marked deficiency of the artificial light in blue, as compared with daylight, makes itself felt when colors in the short wave end of the spectrum are combined with others.

Photo-electric Effects

Sheard and McPeek (88) report extremely interesting measurements on the rest and action currents of the dog's eye. The problem which they attack is that of the existence of antagonistic influences which may be exerted upon the currents of the eye by lights of different colors. Spectral stimuli and a very reliable and delicate galvanometric system were employed. The eyes which were used were always freshly enucleated and care was taken to rest the preparations between exposures to different colors. Constant stimulation produced fluctuations in the nerve current of about 12 seconds period combined with a progressive change in the potential of the nerve stump with respect to the cornea, this change consisting in an increase in the positive potential of the nerve for the warm colors of the spectrum and a decrease for the cold colors, the turning point lying at about $600\mu\mu$. In the case of a yellow, $590\mu\mu$, a conflict of these two opposing tendencies was observable. Complementaries tended to reverse or to neutralize the potential changes produced by each other. When a given potential level has been established by a certain color its complementary produces the greatest obtainable departure from this level. A plot of the potential conditions produced by different wave-lengths shows, in certain of its characteristics, striking similarity to the classical Hering color curves. The fluctuations in potential which were observed were not explicable on the basis of any external causes, and may possibly be related to the fatigue or after-image oscillation processes of the eye. A discussion of the history and theory of the electrical action of light in the retina is included.

Theories of Color Vision

Houstoun (53) offers a restatement and amplification of his theory of color vision previously propounded. This theory is based upon the idea that monochromatic light falling upon the retina gives rise to a nerve current representative not of the frequency of this light alone but, to a lesser degree, of similar frequencies on either side of it in the spectrum, a result of the irregularities of molecular response in the photo-chemical process. The overlapping of such distribution curves for monochromatic red and green is thus able to produce practically the same distribution curve as that given by monochromatic yellow. A sufficient separation of two overlapping distributions, however, will produce two maxima with an accompanying effect of a complex sensation such as purple. The position of the summit of the curve, therefore, is representative of the hue, while its breadth stands for lack of saturation or resemblance to white. An important feature of this paper is a detailed analysis of the color sensation curves of Maxwell, Abney and König and Dieterici, which, for comparison, are reduced as far as possible to the same units. The data of Dieterici are adopted as most representative of the normal and a plot of these data on rectangular coördinates is employed as a basis for developing equations for the trichromatic color system, which are correlated with theoretical equations derived from the writer's hypotheses.

Barton and Browning (11) have investigated mathematically, and with the aid of models, the probable mechanism of the Young-Helmholtz theory of color vision. Three sample resonators of appropriate natural vibration periods were subjected to forced oscillation and their respective amplitudes of response were recorded photographically. The natural periods corresponded to 760, 550, and 400$\mu\mu$ respectively, and the mathematical analysis showed that to produce the resonance curves required by the facts of color vision the vibrations must be very highly damped, this damping being so great that persistence of vision cannot be explained as a result of the continued action of the vibrators after the removal of the stimulus. The theoretical resonance curves differ from those demanded by the facts in not having zero values for any wave-length and in that the red sensation curve shows no second maximum in the violet. The ratios of the responses of the three model vibrators to different impressed frequencies were found experimentally to correlate remarkably well with many facts of color vision, such as the results of mixing various monochromatic lights, fineness of color discrimination in various parts of the spectrum, etc. Lodge (67), Joly (59), and Allen (4) discuss the possibility that the response of the retina to light is photo-electric in nature. Lodge suggests that certain radio-active material which is contained in the pigment cells is set off by light, the resulting secondary rays stimulating the rods and cones electrically. Fatigue is attributed to exhaustion of the radio-active material. He suggests the experimental testing of this hypothesis. Joly reviews two previous investigations of his own on the bullock's eye along this same general line which failed to produce positive evidence. Allen refers to the proposal previously made by him (*Journal of the Roentgen Soc.*, April, 1919) that the response of the rods and cones is due to a photo-electric action at their surfaces, which produces a change in electrical potential and thus generates a nerve impulse. Pikler (77) has propounded an elaborate theory of the chromatic and achromatic colors.

Bard (7) points out that in hemianopia, color vision disappears more readily than form vision, indicating that perception of form is independent of that of color. He propounds the idea that on account of their length in the direction of propagation of the light the retinal rods and cones are able to record directly our impression of the depth dimension of visual space, the retinal image being not a surface but a solid. The pigment cells, lying alongside the rods and cones, serve to record the locus of the image within these receptor cells. The special function of the rods in the peripheral retina is to compensate for the aberrations of the refractive system in this region. Both rods and cones are supposed to be specifically sensitive to all of the colors because the limits of form and color perception are the same. The visual purple is regarded as the essential factor in color perception and its color is supposed to be determined by interference processes within the small disks of which the rods are composed, solutions of the visual purple being colloidal suspensions of rod fragments. Light tends to break up these disks or exert pressure upon them, different colors differing quantitatively in this action. The mechanism of color perception in the macula is attributed to a different process "qui m'a echappe jusqu'a present." Evidently most of the significant results of physiological optics have "escaped" this writer.

Vision in Animals

The year presents us with a number of interesting contributions to the knowledge of vision in animals. Hartridge (43) discusses the significance of the special shapes of the pupil in various animals. The pupil of the cat when partly closed has a longer vertical than horizontal axis, which favors the clear perception of vertical contours, these being of predominant importance to a climbing animal. In the case of the sheep the partly closed pupil has a longer horizontal axis, which harmonizes with the predominant importance of landscape contours for this animal. Being hunted rather than a hunter it needs the increased peripheral illumination along the horizontal axis which is provided by the special pupillary shape.

Rochon-Duvigneaud (83) reports measurements of the positions and sizes of the foveae in five species of *Rapaces diurnes*. The central fovea is usually smaller and deeper than in the case of the human being and the lateral is smaller and shallower than the central one. The thickness of the retina in the region of the foveae is about 170μ. In the buzzard the cones in the center of the central fovea are less than 1μ in diameter but are 65μ long, those of the lateral fovea being shorter. The author doubts whether the lateral foveae in the bird have a binocular or stereoscopic function. He believes that each eye functions separately and that the foveae of the single eye also act independently, much as do the fingers of the hand. In a second article (82) the same investigator gives further details regarding retinal structure in the same birds considered above. He finds that the colored oil droplets are smaller in the fovea than elsewhere corresponding with the decreased diameters of the cones. The colors found are yellow, orange and red, and their functions are probably to form a protective filter. The structure of the birds' fovea is in general finer and more complicated than that of the human being. In day-birds the rod-free region is larger than in man although the fovea itself is smaller. The ganglionic layer is very complex. In the *Rapaces nocturnes* there is only one fovea, which corresponds to the lateral fovea of the *Rapaces diurnes*, and in this there is as large a proportion of rods as in the remainder of the retina, although cones are also present.

Wager (93) reports experiments in which lumps of sugar were utilized on pieces of colored paper to test the chromatic vision of wasps. He finds that these insects are attracted by color and color contrasts. Minnich (70) finds that light stimulates the honey bee to movement, worker bees having a strong positive phototropism. When one eye is blackened the insects move in a loop in the direction of the functioning eye, these "circus movements" varying with the intensity of the light. The constancy of the circus movements shows that the arthropod eye is stimulated continuously by light, not requiring intermittent illumination. Eltringham (31) has studied vision in butterflies, paying particular attention to the nature of the image formed by the compound insect eye and the sensibility of the animals to colors and distances. He finds that objects are distinguished at distances from 3 centimeters to 1 meter from the eye, and contests the view of Hess that insects are color blind.

Hecht presents very interesting data concerning, and a keen theoretical analysis of, the photo-receptor process in a mollusc, *Mya arenaria.* This animal (47) is sensitive to sudden changes in intensity of illumination but comes to a sensory equilibrium at any constant illumination. Its reaction time to light can be divided into two periods, a phase of "sensitization," which is followed by a latent period of 1.3 seconds, during which the stimulus can be removed without preventing the reaction. The laws of adaptation for the animal to any given light intensity can be represented by the formation of a chemical substance according to a bimolecular reaction. Sensory equilibrium is explained in terms of the stationary state of a reversible reaction involving this substance and two precursors. The corollaries of this hypothesis, that the reaction time at equilibrium and the rate of dark adaptation should vary inversely with the temperature were verified experimentally. The author's method of obtaining various sensitivity functions in terms of the length of the sensitization period is extremely neat and is based upon work described in a previous article on another mollusc. In the second paper (48) the same author treats of the nature of the latent period, this interval being too long to be attributed to pure neuro-muscular processes. Experiments made with dark-adapted animals show that if the "sensitization" period is defined as the minimal pre-exposure necessary to produce the minimal reaction time, the latent period will be found to vary inversely as the exposure. It therefore seems likely that the latent period is determined by an independent chemical reaction which is *catalyzed* by the presence of a substance formed during the pre-exposure period. The reciprocal of the latent period must represent the speed of the process which determines it, and this in turn must be proportional to the amount of catalytic substance formed. The essential element in the reaction of the animal to light is, therefore, the formation of a catalyzer or enzyme. The theoretical analysis is extremely keen and convincing. In a third article (49) Hecht considers further the effect of temperature on the latent period. He finds that for temperatures below 21° C. the relation is expressed by Arrhenius's equation but that above this temperature it increases more rapidly. This discrepancy is explained by the conception that the product formed during the latent period is inactivated by heat. The velocity of this inactivation is calculated from the experimental data.

Crozier and Arey (26) have studied the heliotropism of *Onchidium*. In its normal environment the behavior of this animal is independent of light, but under artificial conditions it becomes negatively phototropic. Experiments show that a phototropic tendency exists but is inhibited in the natural environment, this being an instance of a definite response tendency which is non-adaptive in nature and which even tends to interfere with other adaptive actions. Hess (51) describes experiments on the vision of ten different species of crustacea. The writer's earlier results showed the same reactions to colored lights as in the color-blind human being. The differential threshold for intensity in *Daphnia magna* is the same as for man. The writer claims to have determined "visibility curves" for certain crustacea with an accuracy as great as that obtainable for the human eye, by alternately illuminating the animals with homogeneous and heterogeneous light and noting the effect produced upon the swimming movements. The maximal sensitivity for *Daphnia* lies at approximately $525\mu\mu$ and equal responses are obtained at 650 and $450\mu\mu$ respectively. There is no Purkinje effect for these animals and in general they show no sensitivity to color or wave-length as such. Certain species of *Cladocera* are sensitive to ultra-violet light as far as $313\mu\mu$.

White (98) reports experiments in which mud-minnows and sticklebacks were trained to associate food with certain colors, demonstrating that these fishes can discriminate between red and both blue and green and also between yellow and green, although they are unable to differentiate between blue and yellow. To determine whether this discrimination is based upon apparent brightness rather than color, variations in intensity of the several colors were introduced without interfering with the discriminations. These variations were not very great, but the animals showed very little power to differentiate between different shades of gray. They also were unable to base associations upon peculiarities of stimulus pattern.

Arey (5) finds that in the case of two fishes and a frog the retinal rods remain in a shortened condition until an intensity is reached at which ordinary print can be read, while the cones remain elongated until colors can be distinguished. The thresholds for these responses therefore correspond with the utilitarian demands of the functions which they have hitherto been supposed to subserve, although other investigators have expressed doubt on this point.

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Abstracts and Reviews

The Momentary Character of Ordinary Visual Stimuli

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REFLECTION upon the performance of the eyes in ordinary use shows that the instances in which the eyes remain in one position for a period such as three seconds, or even as much as a considerable fraction of a second of time, are rare; or they do not pertain to situations as are implied in the phrase, "use of the eyes." Instances in which the eyes remain stationary or nearly so for gross periods of time are:—

1 Sleep, narcosis, coma and other states, medically known as states of unconsciousness.

2 The condition known as "brown study"—periods of abstraction in which one is caught, perhaps, "gazing into space," and in which, although the eyes appear to be in fixation, the object (if any) upon which they are fixed is, to say the least, remote from the center of attention.

3 The case of the observer in the laboratory where certain experiments in psychology and physiological optics are in progress which call for prolonged fixation. In such cases it is noteworthy that the brightness and color differences in objects tend to disappear, and that troublesome after-images are apt to take place on change of fixation.

4 Also the somewhat unusual case of ordinary vision, including perhaps phases of certain special pursuits, when the object viewed is close to the threshold for the fovea and the observer gazes at it fixedly to arrive at a judgment.

The outstanding fact is, that in the "use of the eyes,"—in sewing, reading, checking and copying, and in "taking in" a drawing or a picture or the lay of a set of objects in space—the eyes are rarely more than momentarily at rest. According to Huey (*The Psychology and Pedagogy of Reading*, New York, 1908) the movements executed by the eyes in reading occupy 0.04 to 0.06 second, while the average duration of the fixational pause he finds to be 0.19 second in one case, 0.11 in another. Dodge (*Zeitsch. f. Psychol.*, lii, p. 373) states that the shortest adequate pauses photographically recorded in one of his experiments are 0.070 to 0.100 second. Certainly is this true of such work as is commonly accounted as "trying" to the eyes.

It is due to Troland, (*American Journal of Psychology*, 1914, xxv, pp. 500-27; *Transactions of the Illuminating Engineering Society*, New York, 1916, No. 9, pp. 947-66, and *Journal of the Optical Society of America*, i, 1917, pp. 3-15) starting from Hering's viewpoint, that the development of a new phase of the theory of vision has been forwarded, in which the change of state of the retinal elements is given first importance, and the conception of the (so to speak) one to one representation of stimulus-brightness in retinal response has been pushed into the background. Upon this hypothesis, granted that a stimulus of constant intensity continues to fall upon the same retinal area, the physiological condition in that area tends toward a certain state of equilibrium and approaches that state at a rate greater according to its remoteness from that state, somewhat after the manner in which the temperature of a body tends toward the temperature of the medium in which it either takes on or loses heat. Removed to a medium of different temperature, the body will at once tend toward the new temperature, by the same law, at a rate proportional to the temperature difference.

Similarly with the retina. The temperature of the medium represents that particular state of physico-chemical equilibrium in the retina which would hypothetically be induced by the continued action of the constant stimulus; a terminal state which the retina can, under constant conditions, be conceived to approach indefinitely without reaching it in any definite time. A new stimulus acts, and the retina begins a change of state, initially from whatever state it is in, toward a new terminal state; the initial change being the more rapid the more remote the new terminal state and *vice versa.*

But with the saltatory behavior of fixation, which has been well demonstrated by photographic records of the eye-movements executed in reading, no part of the retina—or at least not all parts critical in recognizing a given detail—can be conceived to reach a state of equilibrium, unless by way of a rare exception. The rule will be that a given retinal element only begins to make a change toward a certain state, when the process is cut short by a shift of fixation, before a state of equilibrium is even approximated.

Now what happens when, as in most experiments on visual thresholds, a part of the retina of a fixated eye is subjected to stimulation for one-half or one or several seconds? And what bearing has this on what happens to the retina in the case in which such a stimulus is cut off in a few thousandths or hundredths of a second? Obviously the two occurrences bear a certain mutual relation, but the latter represents the initiation of a change while the former represents more nearly the final stages of the same sort of change; the former is a type of stimulation whose result must be conceived to depend more largely upon the terminal state corresponding to the continued action of the stimulus, while the latter will give a result depending upon the quickness of the retina to respond, a result which, I believe, is more truly representative of the behavior of the sense-organ in the course of its every-day performance.

By way of thesis, for experimental verification or refutation, the following may be laid down:

1 Every-day vision involves, as a rule, only momentary fixation, during which most of the details of the total impression are taken in, not by the fovea, but by the parafoveal

retina. Possibly the peripheral retina is best adapted to momentary stimulation. At least it may be said that the peripheral retina is highly sensitive to change of stimulus; and also to movement, which, when analyzed as a stimulus, resolves itself into changes of stimulation of retinal elements.

2 The adequate stimuli to such vision are *a priori* by no means identical with those adequate to the foveal retina, especially when in the latter case the time of exposure to the stimulus is one of longer duration, as in the practical vision of a barely-visible object.

3 The conditions of eye fatigue and eye-strain are to be sought, not in relation to the unusual and more or less episodal performances of the eyes; but rather in relation to such performances of the visual organs as are the rule in the course of their ordinary use.

In detail, such performance of the eyes as is the rule in typical eye-work, as in reading for example, consists in successive momentary fixations, in which details of the words and of the letters forming them are impressed chiefly upon the parafoveal retina; and in sudden leaps from one point of fixation to the next, during which it seems probable that no neural impulse originating in an impression upon the retina is able to take part in the sensory integrative process.

(Abstracted from *Psychobiology*, Vol. II, 237-244, 1920.)

Some Factors in the Perception of Relative Motion

H. C. Carr and M. C. Hardy

THE perception of motion is relative. The observer perceives the motion of one object in relation to some stationary object or set of conditions. In the perception of motion an appreciation of the stability of the one object is just as essential and important as the appreciation of the motility of the moving object. The observer himself constitutes the center of reference in most perceptual acts.

The perception of motion involves two aspects; an appreciation of the fact of motion, and an appreciation as to which of the two objects is stationary and which is in motion. These two aspects are to some extent independent variables. One's appreciation of them may be based upon entirely different sets of conditions. One may correctly perceive the fact of motion, but judge erroneously as to which of the two is moving. If a fixated visual object is moved toward an observer, there results a change in the sensory conditions which mediate his judgment of distance. But exactly the same changes will be induced by a movement of the observer toward the object. Changes of these distance criteria, as intensity, size of retinal image, accommodation and convergence, etc., serve to induce in both cases an appreciation of a change of the distance between the object and the observer,—an appreciation of the fact of motion. But these sensory changes give no clue as to which object moved and which was stationary. Judgments of the relative motility of the object and the observer depend upon other factors, presumably certain characteristics of either one or both of the two objects concerned.

When the organism constitutes one of the objects in the perceptual situation, the judgments concerning the motility-stability relation are based in part upon certain sensory aspects of the observer. The judgments of relative motion are based upon the presence or absence of such factors as the intention or expectation of moving, the sight or feeling of muscular activity, friction, air currents, the static sense, organic sensitivity. As a rule these factors mediate correct judgments.

The experiments described in this paper were conducted for the purpose of finding the possible influence of certain features of the objective situation. The observer was seated in a dark room and was required to judge as to the relative motion of two small lights whose intensities were such that no other objects were visible. It was hoped that the judgments might be based mainly upon certain characteristics of the two lights rather than upon any perceptible relation between them and the observer. Two 2 c. p. lamps were each enclosed in a box with suitable openings; each box was placed upon a horizontal double rod track. By an appropriate device either one or both of the light boxes could be easily and quickly attached to or disengaged from a moving piston system operated by a motor. The motion imparted to the lights was thus a vibratory or pendular one. The main conclusions of the paper are:

1 Perceptual accuracy was promoted either by a difference in size of the two lights or by an increase in their combined area. Possibly both conditions may have been operative.

2 Perceptual accuracy was favored by an inequality of brightness of the two lights and by a decrease of their combined illumination.

3 The amplitude or extent of motion so far as this factor was varied did not exert any effect upon perceptual ability.

4 Perception was generally more accurate with the faster rates of motion.

The individuals exhibited consistent differences in their ability to perceive the situation correctly.

5 The majority of the subjects were able to perceive the situation more correctly with stationary eyes, *i. e.*, when the stationary light was fixated and the moving light was perceived with indirect vision. Some individuals gave the better records when the moving light was fixated. Other individuals were able to judge equally well for both conditions of fixation.

6 Some individuals were able to perceive more correctly when the stationary light occupied the upper position, while the opposite condition obtained for other subjects. The position of the stationary light was not effective for other observers.

7 The influence of fixation indicates that certain individuals

solved the problem in part by an indirect reference of one of the objects to the organism. It is practically impossible to exclude all spatial reference of the objects to the observer. Some subjects were apparently able to detect the moving object by means of the eye sensitivity involved in following it. Others were able to identify the stationary object by the absence of eye-movement while fixating it. Individual differences in this respect do not admit of a ready explanation.

8 The influence of the position of the stationary light may be explained by the supposition that the subjects apprehended the perceptual situation much as though the two lights constituted the ends of a swinging pendulum. Individuals who exhibited any tendency to conceive the situation as similar to a simple suspended pendulum would obviously associate the upper position with stability and hence would make a greater number of correct judgments when the stationary light occupied this position. On the contrary those who preferred to regard the situation as analogous to a metronome would associate the lower position with immobility and give the better records when the lower light was stationary. Certain subjects were not influenced by the position of the stationary light. This fact may be explained by supposing that these subjects conceived the situation as a compound pendulum with the center of rotation located between the two lights, that they were able to assume equally well either of the first two attitudes, or that they failed to adopt any pendular attitude.

(Abstracted from *Psychological Review*, Vol. 27, p. 25-37, 1920.)

Dark-Adaptation

Percy W. Cobb, Captain, M. C.

THE full title of this paper is "*Dark-Adaptation with Especial Reference to the Problems of Night-Flying.*" The immediate investigations reported upon were undertaken with a view to designing a method whereby the visual fitness of the aviator for night-flying could be tested. This research has, of necessity, developed many interesting points on absolute sensitiveness and rate of recovery after the relative blinding following exposure to light for short periods. These are the matters of interest to the reviewer.

In the course of an hour spent in darkness the sensitiveness of vision for light increases gradually and may attain a value several thousandfold that initially found. In order, however, to be certain that an observer has reached the standard and reproducible condition, it is necessary to measure the light sensitivity from time to time. When the uniform condition has been reached the subject is in shape for further experimentation.

The test for light-sensitiveness is, in the first instance, the photometric brightness of a surface which is just visible with certainty. The adaptometer is an instrument for maintaining and measuring the photometric brightness of a surface. The one used by the author was built on the fundamental principle proposed by Nagel (*Zeitschrift für Augenheilkunde*, 17, 3) with certain technical modifications. Essentially it consists of an optical system for projecting the test pattern on to a translucent screen. The test pattern consists of a pair of bars cut in a disc which can be rotated to any desired pattern or else of two sets of bars, one set being vertical and the other horizontal. Directly above the test pattern and on a level with the eyes of the observer was fixed a fixation-point. This fixation-point was kept just bright enough to be located in the dark. Finer changes in the adjustment of the brightness of the test pattern were secured by means of an absorbing wedge.

In carrying on the investigations in dark-adaptation, the subject was seated before the adaptometer and fixated at the red-fixation-point. The shutter of the adaptometer being opened for one second, the subject was tested as to ability to see the test pattern and locate its position correctly. The time and scale reading (brightness) was recorded and such determinations continued until standard and reproducible conditions obtained when the eye was known to be dark adapted.

When this point was reached a white screen was placed before the eyes of the subject, leaning against the front of the adaptometer at a definite inclination; and the center light of the room was turned on. The subject was instructed to maintain his position and direct his eyes toward the center of the screen. In preparation for what was to follow, the test stimulus, set at a certain point, was exposed by drawing the shutter. Five minutes from the time the light was turned on, the screen was quickly removed and the light turned off after an interval of perhaps one or two seconds in which the observer could locate the fixation-point. He remained at this fixation until the test stimulus, at first invisible owing to the five minutes blinding, became visible to him. The time required for this to take place was noted. Subsequently readings were taken as before, but somewhat more frequently, until the former absolute threshold was again reached.

Finally, the white screen was replaced and the procedure of the last paragraph repeated with fifteen seconds exposure to the white screen, in an exactly similar way. From the time the subject entered the room until the end of this third portion of the experiment the whole procedure occupied from an hour to an hour and a quarter, according to the speed of the subject in recovering his absolute threshold.

The screen used for "blinding" the subject was a sheet of white blotting paper 24 by 19 inches, mounted on a light frame. Its angle of inclination and distance from the eyes were such that it subtended, at the eyes, an angle of 67 degrees vertically and 70 degrees horizontally in respective planes through its center. Its lower half was nearer the observer, consequently including a larger angle, easily including the part of the visual field occupied by the test-stimulus and much more in every direction. The photometric brightness of this screen averaged 13 candles per square meter by actual measurement.

The various values for sensitiveness were plotted, each against the time at which it was obtained. Thus each experiment yielded three curves as in Figure 1. The first of the three began with the state of adaptation in which the subject happened to be and was carried on until his absolute threshold had been reached. This was taken as one datum in his case.

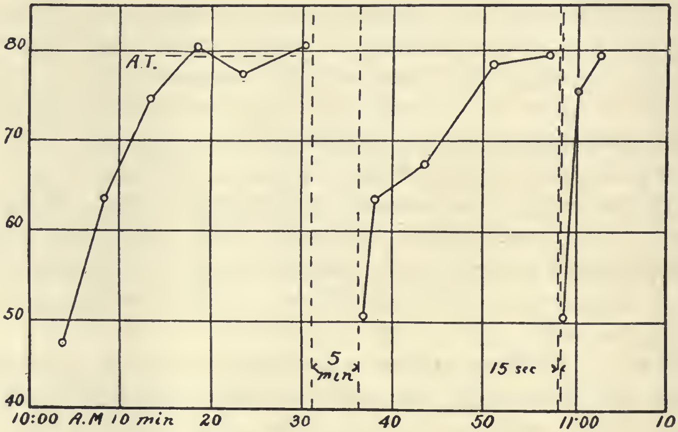

Fig. 1. Specimen plot of one experiment. The first curve was taken without preparation. In this case the mean of the last three points (79.5 mm.) was taken as the absolute threshold, and its location on the plot is indicated by the horizontal interrupted line. The two blinding periods are indicated by the vertical interrupted lines. The return of both curves to the exact value of the mean absolute threshold is simply coincidence; usually there is some discrepancy.

The second curve represents his recovery after five minutes blinding by a surface of standard extent and brightness. Here the question was rather his rate of return to dark-adaptation than the ultimate point. The first datum here, in the chronological course of the experiment, was the time required to see an initial stimulus, already exposed when the room was darkened, as his dark-adaptation progressed and the sensitivity of his vision grew sufficient to take account of it. At this stage the increase in sensitivity is rapid, for which reason the technic just described was made use of.

After considerable experimentation, the author selected the following tests:—(1) The absolute threshold. (2) *a.* The time required to reach an arbitrary, rather low degree of sensitiveness, obtained by noting the instant that the test stimulus appears to emerge from the darkness. *b.* The time required to reach an arbitrary level (70 mm. on the scale) obtained by linear interpolation from the curve of rise. *c.* The time required for the individual to reach a point on the scale 15 mm. short of his own absolute threshold.

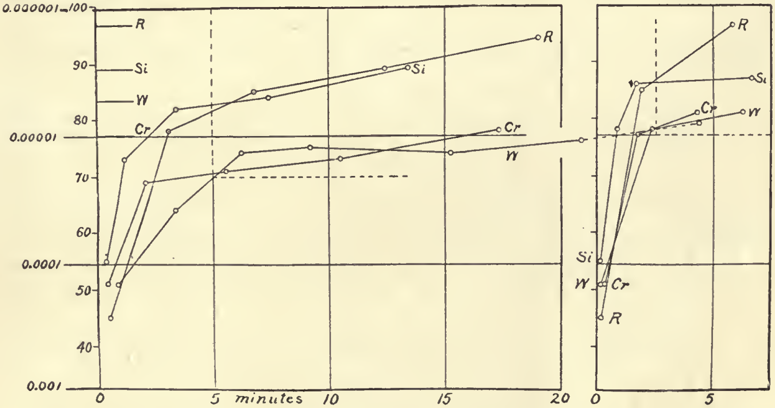

Fig. 2. Four cases showing typical courses of adaptation as to extent and rate: *R*, high sensitivity, slow recovery, *Si*, same, rapid recovery; *Cr*, low sensitivity, rapid recovery, *W*, same, slow recovery.

On the left, after 5 minutes blinding, on the right after 15 seconds blinding.

The absolute thresholds, previously taken, are indicated near the upper left angle of the figure.

Examination of all of the curves and data shows the possibility of dividing the course of adaptation into two portions: The early abrupt rise out of the relatively blinded state and the late, slow approach to the absolute threshold. The tentative limits are indicated in the plots (Figure 2) by the dotted lines—in the case of the 5 minutes blinding all observations after 5 minutes and above 70 mm. on the scale being crossed in the latter portion of the curve. Figure 2 gives the data on four cases showing typical courses of adaptation as to extent and rate: *R*, high sensitivity, slow recovery; *Si*, same, rapid recovery; *Cr*, low sensitivity, rapid recovery; *W*, same, slow recovery. The left figure shows the results after 5 minutes blinding; the right after 15 seconds blinding.

In further comment on his work, the writer says: "It is possible that the sudden onset of the rather bright light, after complete dark adaptation, may, so to speak, surprise the

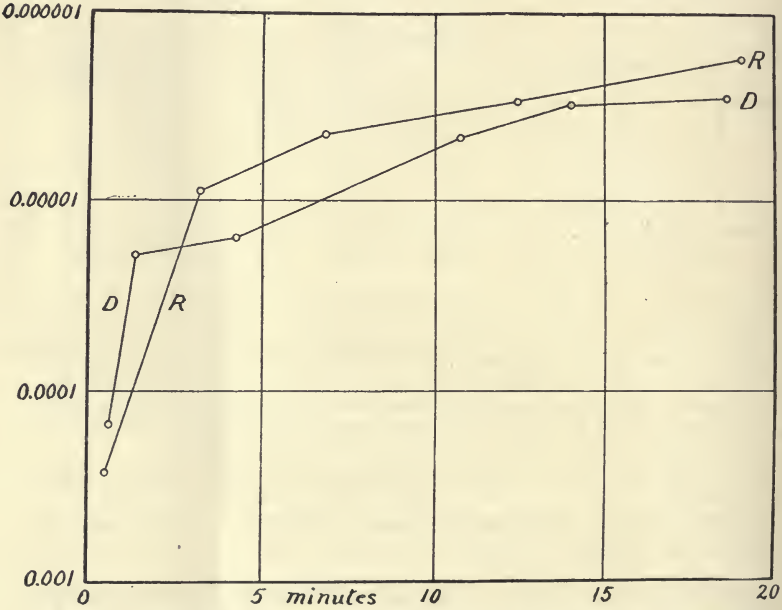

Fig. 3. Two types of adaptation curve. *R*, "normal" or regular form. *D*, irregular form showing a halt within the first five minutes and subsequently a more rapid rise.

visual apparatus into more profound changes than would be induced by the same exposure to light applied with gradual onset under similar conditions. Aside from the changes in the size of the pupil there are two anatomic factors undoubtedly concerned in dark and bright adaptation: the exhaustion and regeneration of the visual purple (or possibly other unknown photochemical substance); and the migration of the pigment of the hexagonal cells. This latter may be a protective device that acts fairly promptly, and has the effect of enclosing the retinal rods and by its own light-absorbing qualities reducing the amount of light absorbed by the individual rods. It is conceivable that a sudden flash of light might anticipate this action and produce a strong destruction of the photochemical material in a short time, before the pigment cells have had time to react, while with gradual onset of light the time is adequate for the pigment cells effectively to assume this protective function."

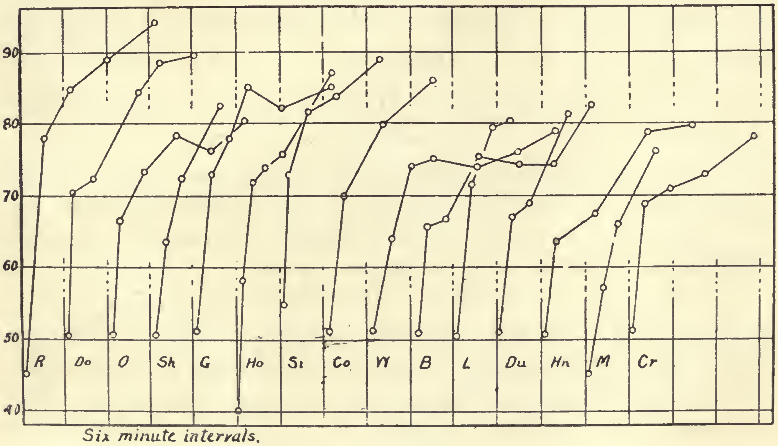

Fig. 4. The course of adaptation after 5 minutes blinding in 15 different subjects. The vertical line in each case is the zero ordinate for the corresponding curve, indicating the instant the blinding period came to an end and the dark-adaptation began. These ordinates are arbitrarily plotted six minutes apart.

Some of the curves strongly suggest two factors playing a part in dark-adaptation. In Figure 3 one of these is shown together with a typical smooth curve. Any attempt to smooth out D's curve here would have to proceed on the assumption of large experimental errors at the second and third stations; or else the results would have to be interpreted as arising from two more or less independent mechanisms one of which overtakes the other, in effect, at the end of about four minutes. Such terrace-like irregularities, which may be interpreted as a halt in the progress of dark-adaptation, are present in 14 out of a total of 52 adaptation curves taken, and are suggested in four others.

Summary

1 Upon investigation of fifteen subjects it appears that the limit of vision in dark-adaptation (absolute threshold), measured by the least brightness at which gross form may be recognized, is variable within extreme limits expressed by the ratio of 7.4 to 1. These limits lie between 1 and 10 millionths of one candle per square meter.

2 The rate of recovery, after dark-adaptation is disturbed by a standard exposure to light, is also variable as between individuals and by no means always in a sense corresponding with the value of the absolute threshold. The extremes of variation between individuals as to time of recovery are as 4.5 to 1 and as 2.5 to 1 for a longer and shorter period of blinding respectively. Recovery, as here used, means the individual's return to a definite multiple (by the factor 4.7) of his absolute threshold.

3 The time of recovery to the point of distinguishing a test-object of standard brightness is to be looked upon as a function of both of these, the one or the other preponderating in effect according to the test stimulus chosen. For a test stimulus 4.7 times the (geometric) mean absolute threshold of all observers, the extreme variations in time are expressed

as 8.7 to 1 and 2.75 to 1 for a longer and a shorter period of blinding respectively.

4 The times of recovery are less diverse after a short blinding (15 seconds, 13 candles per square meter) than after a longer one (5 minutes, same), and in the former case recovery takes place, on the average, in about one third the time, or probably less when all antecedent conditions are equalized.

5 The occurrence, in the course of dark-adaptation, of more or less definite arrests in the decrease of the threshold suggests the independent working of two physiologic mechanisms. These halts occur, more or less definitely, 18 out of 52 courses of dark-adaptation investigated, and appear as more or less definite "terraces" on the slope of the curve.

(Abstracted from *The Psychological Review*, Vol. 26, No. 6, pp. 428-453, 1919.)

Some Theoretical and Practical Points in Refraction Work

Alexander Duane, M. D.

THE author brings together some facts in physiological optics that bear on the theory and practice of refraction. Amongst the important points are:

Theoretical Points

Cardinal Points. The principal significance of the cardinal points is shown in the following:

1 The position of the posterior focus with relation to the retina determines whether the eye is emmetropic, hypermetropic, or myopic.

2 The position of the posterior nodal point with relation to the retina determines the size of the retinal image and has, therefore, a bearing on the apparent size of objects and on visual acuity.

3 The main effect of glasses placed in front of the eye is not to change the refractive power of the latter but to shift the position of the cardinal points—putting the posterior focus of the eye (F) on or off the retina and changing the position of the posterior nodal point (K) with relation to the latter.

4 If a glass is placed at the anterior focus of the eye—and this is the regular place for correcting glasses—it makes absolutely no change in the refractive power of the eye. That is, a +10 D. lens placed 14 mm. in front of the cornea has no effect whatever on the posterior focal distance of the eye which remains 21.1 mm. What it does do is to shift the posterior focus of the eye and also the posterior nodal point of the eye some 3 mm. forward and thus exert a marked and determinate effect on the clearness of retinal images.

5 On account of this and other properties, the anterior focus of the eye is the point where we should place glasses to be worn, where we should place the ophthalmoscope in applying the direct method, and from which we should make our measurements in determining the far point and near point of accommodation.

Effect of Posterior Surface of the Cornea on the Refractive Power of the Eye. Measurements and calculations by Tscherning show that:—(1) the posterior focal distance is 20.79 mm. if we disregard the posterior corneal surface, (2) the posterior focal length is 21.14 mm. if we regard the effect of the posterior corneal surface and (3) the difference corresponds to a difference of a whole dioptry in refraction.

Standard Eye not Hyperopic. The author does not believe there is any data indicating that the standard eye is hyperopic instead of emmetropic.

Change of Refraction in Development of Eye. The facts indicate that, as the child's eye develops, the excessive curvature of the lens diminishes, causing a reduction of the curvature myopia, and the eyeball elongates, causing a reduction of the axial hyperopia. As a rule, the latter process predominates so that the eye as a whole tends to grow less hyperopic and tends toward emmetropization.

Astigmatism. Attention is directed to the researches of Gullstrand which show that the familiar conceptions of our text-books showing Sturm's conoid and Sturm's interval are only rough notions of astigmatic refraction. Gullstrand has shown that the diffusion images formed by a sphero-cylinder are not the regular ellipses and lines ordinarily pictured but are stellate figures. The manner in which the light is concentrated in this diffusion images is the chief factor controlling clearness of vision.

Ophthalmometric determinations are discussed and the point is clearly made that the ophthalmometer determines the radius of corneal curvature at the point of examination and hence determines the astigmatism only by inference on the basis that, first of all, the refractive state of the various media behind the cornea is of a certain character and, secondly, that there is no cause for the corneal astigmatism other than the unequal corneal curvature.

Lens in Accommodation. The exhaustive analysis of Gullstrand has furnished further proof of the essential validity of Helmholtz's theory of accommodation and demonstrates that the lens during accommodation not only changes its shape but also becomes more refractive in that the total index of refraction is greater in accommodation than when at rest. In accommodation the lens increases 11 per cent in thickness; the curvature of the anterior surface increases 87 per cent and that of the posterior surface 12.5 per cent.

The author discusses the view of Hess and others that the ciliary muscle has practically the same contractile power in childhood, youth and middle life, so that it is able to put forth the same accommodative effort at one age as another. The claim is made that, on Hess's theory, homatropine ought to produce a noticeable effect very quickly in children, much later at the age of twenty or twenty-five and very late, if at all, in persons over forty. The tests of the author show that paralysis from homatropine becomes evident about as quickly in the older person as in the child.

Practical Points

The Use of Cycloplegics. The writer believes that, in the great majority of cases, the refraction of the eye cannot be determined with certainty, without the use of cycloplegics, saying that this applies more to astigmatism and hyperopia than to myopia. The author discusses the various objections raised against the use of cycloplegics and gives the results of his own experiences and the weight of his opinion as in favor of their use. This is also his belief in cases over forty, for he uses cycloplegics in nearly all cases up to forty-eight because he believes that those of middle life often relax the accommodation imperfectly or with great difficulty. The writer gives some valuable instructions as to methods of testing whether or not complete cycloplegia exists. The test is a simple accommodation measurement. When with a +3 added, the far point is found to be at 3 and the near point at 3.75, the range of accommodation is evidently reduced to less than a diopter.

A very valuable test—irrespective of the use or non-use of cycloplegics—is given by the writer in the following words:—"When the manifest correction in each eye has been obtained and apparently no further relaxation of the accommodation can be secured, I put on the glasses found, direct the patient to look with both eyes and then add to this binocular correction convex glasses by successive increases of +0.25 D. Patients who have refused to take any further addition in monocular vision, may, when looking with both eyes, be led to accept as much as a dioptry or more of convex correction. The addition is made to both eyes simultaneously until blurring begins."

Necessity of Accommodation Tests. Repeated tests should be made of the accommodation. Insufficiencies of accommodation are of great importance at all ages, though particularly in the young, and if they are not recognized and treated, the results of the correction of the refraction may be disappointing. Testing of the accommodation is of particular importance in insuring proper presbyopic correction. Quite often an unequal maximum of accommodation is exhibited in the two eyes.

Necessity of Careful Muscle Testing. "So too, the determination of the muscle balance, for far and especially for near points is of great significance in our refractive work. In the presence of a convergence excess we crowd our hyperopic correction. In the presence of a convergence insufficiency, evidenced by a marked exophoria for near and a remote convergence near point, we are careful not to give a strong presbyopic correction, which in just these cases is badly tolerated. In cases of hyperphoria we may have to add a vertical prism or in certain cases a prism paster to ensure comfortable vision. And sometimes the proper glasses can be made tolerable only after a proper course of muscular training. Some cases can be made comfortable only by operation."

Factors Governing the Treatment of a Refractive Error

1 *Age.* Symptoms in children do not have the same significance as in adults. The author recommends caution in giving correcting glasses to children, even though "hyperopic of a dioptry or more and astigmatism of 0.50 D" be found. Myopia he believes should have a full correction at once, since it is the best means of preventing the increase of near-sightedness. (With all of which, many facts and the practices of many of the most skilled men are strictly at variance. ED.)

2 *Vision.* Care is advocated to the extent of "getting the glasses right to a 0.12 D." in "patients who have sharp vision for distance and who make sharp distinctions."

3 *Amount and Kind of Use to which Eye is Put.* Considerable tax is laid upon a pair of eyes when:—(a) Engaged

in hard continuous work under trying conditions, (b) looking at moving objects, objects in theatres, etc., (c) engaging in certain occupations, as proof-reading, etc. in which discrimination of detail occurs, (d) engaging in work largely under artificial light.

4 *Symptoms and their Obvious Relation to the Use of the Eyes.* In prescribing glasses one is likely to make two mistakes. First, symptoms which are not of ocular origin may be attributed to the eyes, but may be due to nasal obstruction or dental infection. Secondly, there is a considerable difference between individuals with reference to their reaction to strain of any kind.

5 *The Accommodation and Associated Muscular Conditions of the Eyes.* In many cases it is difficult in the presence of a muscular anomaly to tell whether this or the refractive error is the cause of the symptoms. In such cases the author advocates the correction of the refractive error only at first.

6 *Associated General Symptoms and General Condition of the Patient.* The influence of the patient's general condition on his ability to do eye work is obviously important and should be carefully considered. "A patient depressed by overwork or in other ways may develop eye symptoms, the relief of which may require both treatment addressed directly to the eyes and treatment designed to remove the cause of the systemic trouble. Patients who are mentally depressed or mentally backward and patients who are nervous or supersensitive require special care in examination and special attention in treatment. The relief of their eye condition may be an essential element in their improvement and we must give our best efforts to secure good results in this regard. At the same time in our zeal to correct the eyes we must not forget the individual and his idiosyncrasies nor the fact that the correction of his other physical and his nervous ailments claim equal attention with the ocular treatment."

(Abstracted from *Archives of Ophthalmology*, Vol. XLIX, pp. 349-366, 1920.)

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Hysteropia, or the Ocular Manifestations of Hysteria

Thomas Hall Shastid, A.B., A.M., M.D., LL.B., F.A.C.S.

THE protean disease which is called hysteria makes known its presence by numerous ophthalmic disorders. The most of these may greatly complicate the work of the refractionist, and all of them are interesting.

First comes *madarosis* (or *alopecia*) *ciliaris*. The cilia, it seems, are simply pulled out by the patient. Hence the baldness of the lids.

Paralysis of the levator palpebrae superioris seldom, if ever, occurs. At least I never have seen a case. But *hysterical blepharospasm* (spasmodic closure of the lids, with inability, at least for a time, to open them) is not uncommon. All the cases which I have noted were accompanied by extraordinary susceptibility to hypnosis, and one of them was cured by a single application of this remedy.

Palsy, as well as *spasm*, *of the various extrinsic muscles* of the eyeballs, occurs, but is very uncommon. I have seen two cases of internal squint which, beyond question, were hysterical.

Hysterical cyclospasm (tonic contraction of the ciliary muscle) is common indeed. The muscle, being in a rigid condition, is too much contracted for distance, too little for near. The peculiar consequence is that the patient apparently requires a convex glass for near, a concave for distance. If, however, the glasses are prescribed, the muscle proceeds forthwith to vary its spasm, and the glasses suit no longer. Even if atropine be first employed, and the patient's exact correction is determined, even then, when the effect of the atropine has passed, the spasm of the muscle returns, and lo! once more the glasses, which were fitted with however great care, are found to be unsuitable.

Cyclo-paralysis is also common. The patient, even if very young, is apparently presbyopic—sometimes, if the cyclo-paralysis be complete, as much as three dioptries. Fit the patient with glasses, and, like as not, in a few days, she returns with the information that she sees much better without them.

Monocular diplopia and *polyopia* are extraordinarily common in hysteropes. These conditions must, however, be grubbed out by the diagnostician. The patient herself, as a rule, is not cognizant of their presence.

Nystagmus in hysteropes is rare. At all events I never have seen a case. Hysterical *hippus*, however, I have observed.

Defects in the visual field are so common in hysteria as invariably to be thought of in connection with this disease. Commonest of all are the so-called concentric contraction and the reversal of the fields for colors. Concentric contraction means simply that the field-periphery in general has contracted and with at least a certain amount of symmetry *i.e.*, the contraction at each and every portion of the field-periphery is substantially the same. The longer the examination is continued, the more contracted the field becomes. In fact any contraction of the field seems to be the result of suggestion acting upon the patient's mind. Now as to the *colors*. As is very well known, the visual field is normally more extensive for objects of some than for those of other colors. As to the normal eye, the most extensive field is that for white. Next most extensive, blue; then red; then green. Note that the order is not that of the spectrum, nor yet the reverse. Why, precisely, this order of the color-limits in the field? Nobody knows. In hysteria, however, the order of the color-limits is the reverse of normal. And once again the reason has never been ferreted out. One cannot say that the reversal is due to suggestion, for the patient, unless herself a physician, does not even know what the normal color-limits are. Instead of white, blue, red and green, the order, in hysteria, is green, red, blue and white. To test the color-limits properly, the illumination must not be too strong. The reason is that the blindness for the various colors in the outer districts of the field are not absolute, but relative. This is true, even of the normal eye. Increase the illumination sufficiently, and all the colors are clearly perceived even to the farthest limits of the white-field.

A common affection of the central field is fluctuation of the *visual acuity*. When first the patient is examined, she may have substantially normal central vision. Then the acuity diminishes. On re-examination, it diminishes still further. Then further still. And so on, until, if the attempts to test the eyes are continued yet longer, the sight may die away completely. After a little, of course, it returns.

There may also be *paracentral color scotomata*, and *quadrant defects*.

Hysterical amblyopia and *amaurosis* are known to everyone. Amblyopia is blunt vision and amaurosis no vision—both being independent of errors of refraction. These affections are, as a rule, bilateral. I had, however, a troublesome case in which the patient was stricken with sudden blindness in one eye, a blindness which had been attributed by a fellow practitioner to embolism of the central artery of the retina. I could find no fundus changes, and declared the case to be hysterical. An acrimonious discussion was the consequence between the parents of the girl, one of the parents declaring for hysteria, the other for embolism. To settle the matter, the girl got suddenly well.

Inasmuch as hysterical amblyopia and amaurosis often follow injuries, they become, in consequence, troublesome bases for damage suits. Correct differential diagnosis and a speedy cure are essential. A little tact, a little treatment, a good deal of suggestion, and the trick is turned, as a rule. Sometimes a single word will banish stone blindness. I have had such a case. The greatest mistake is, of course, to treat these traumatic hysteropes as base imposters and thieves.

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The Optical Center of a Lens

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IT is very commonly, though erroneously, assumed that the optical center of a simple ophthalmic lens is an axial point located either upon the lens surface or within the lens medium, and consequent to such view has been the practise —when a lens is centered upon a lens centering device—of affixing upon the lens surface at its intersection with the instrument axis an ink dot, designated as the optical center of the lens. The very close approximations to accuracy which such procedure allowed when bi-spheric lenses were in exclusive use sanctioned acceptance of this theory and practise although it seems not to have been realized that the axial point thereby determined represented the pole of the lens and not its optical center. The advent of the periscopic form of lens, with its ever shifting optical center, has demanded a modification of this practise, since the lens form is not without important influence upon the axial position of this point.

To facilitate lens manufacture and measurement it has for long been universally agreed that the lens surfaces shall be dissected by imaginary meridian sections intersecting at a common point upon the surface and such point has been designated the pole of the lens. This point being the common intersection point of lens axis and meridians is essentially a geometric point and its confusion with the optical center, which is an optical image point based upon known optical laws, should be guarded against. Always upon the lens surface will be found the pole of the lens; never, however, may such generalization be extended to include the optical center, which is never located upon the lens surface except in plano-spheric lenses and then only upon the spherical surface.

Prevalent also has been the view that each meridian section of the lens is related to a common optical center and it will be the endeavor in this article to show that such view is tenable only when applied to lenses of spheric surfaces and never to those of sphero-toric form.

The position upon the axis of the optical center of any lens is a function of the location of the nodal points, the latter being understood as those axial points at which the angular magnification is unity. The incident and emergent chief rays intersect the axis under equivalent angles at these points, a new angle being determined upon entrance of the incident ray into the lens and upon the latter angle the position of the optical center is dependent. Alteration in the slope angle of the chief ray demands a new intersection point upon the axis and this axial point or optical center will be found conjugate to the above defined nodal points. The location of that axial point, therefore, conjugate to the nodal points of the lens, constitutes a determination of its optical center and constancy in position of this point may never be assumed. Each transition from one lens form to another demands corresponding migrations of the nodal points upon the axis entailing, in consequence, proportional alterations in the position of the optical center. As applied to a meniscus and contra-meniscus lens the following diagrams graphically portray this condition.

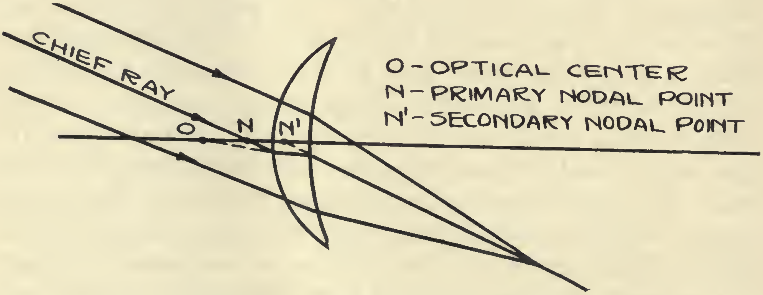

Fig. 1. Illustrating optical center, convex meniscus.

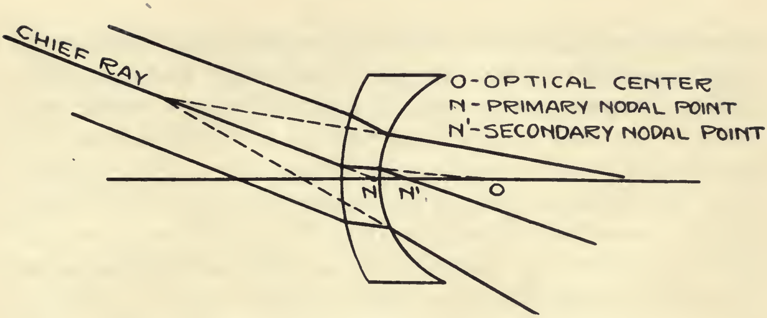

Fig. 2. Illustrating optical center, concave meniscus.

To substantiate the conditions alluded to in the above diagrams the following mathematical relation deduced from simple optical laws will be presented and interpreted.

$$A_1O = (\sigma_2/\sigma_2 - \sigma_1)\ d$$

wherein:

A_1 = Anterior pole of lens
O = Optical center
σ_1 = Curvature of anterior surface
σ_2 = Curvature of posterior surface
d = Axial thickness of lens

All distances upon the axis from the pole of the lens are here considered negative when contrary to the light's incidence, which is assumed as passing from left to right.

Inspection of the formula will show the dependence of the point O upon the magnitude and sign of the quotient $\sigma_2/\sigma_2 - \sigma_1$. No constant value exists for this factor and in sign and magnitude it adjusts itself to what the lens form demands. Possessing as inherent to its construction an anterior surface curvature of greater value than the posterior, the meniscus lens will demand for the quotient $\sigma_2/\sigma_2 - \sigma_1$ a negative sign and a value less than unity, thereby locating the optical center in the medium anterior to the lens and at a distance from the pole equivalent to a fractional part of the lens thickness. The contra-meniscus lens designed upon a posterior curvature of greater value than the anterior demands a positive value greater than unity for the above quotient locating, therefore, the optical center within the medium posterior to the lens and at a distance from the anterior pole proportional to the magnitude of this quotient. Since all bi-spheric lenses are essentially constructed upon surface curvatures opposite in sign, the quotient $\sigma_2/\sigma_2-\sigma_1$ assumes a positive sign and a value less than unity whereupon the optical center becomes located within the lens medium and at a distance from the anterior pole proportional to the magnitude of this quotient. It is obvious, therefore, that associated with each lens form will be found a distinctive position for the optical center and it is erroneous to assume that this point maintains a constant position upon the lens surface or within the lens medium for all ophthalmic lenses. The pole of the lens, it should be noted, maintains such position upon the lens surface, being in no way influenced by lens curvatures and thickness.

Application of the above formula is rigidly restricted to a meridian section of the lens and in those instances in which such sections are of uniform curvature, as in spherical lenses, a single common optical center will exist upon the axis. It is not generally known, however, that upon the axis of the sphero-toric lens no optical center exists since, as an inherent feature in its manufacture, it is possessed of meridian sections of varying curvature. Such point becomes replaced by a line segment upon and coincident with the lens axis and terminated at either extremity by the optical centers corresponding to the two chief meridian sections of the lens, its magnitude being determined by the power of the cylinder incorporated into the lens. That such modification of the optical center would have resulted might even have been presupposed since representation of point objects by line images is a characteristic feature of astigmatic lenses, although the utilized lens aperture is without influence upon the magnitude of this line segment. These facts may be exemplified by a determination of this line segment in the following lens designed upon the usual 6.0 D toric base curvature. Lens thickness 3 mm. + 2.00 D.S. ○ + 3.50 D.C. axis 90°.

In the 90° meridian section:

$$A_1O = (8/8 - 12)\,3 = -6.0 \text{ mm.}$$

In the 180° meridian section:

$$A_1O = (8/8 - 19)\,3 = -2.2 \text{ mm.}$$

The optical center corresponding to the 90° meridian section lies therefore upon the axis and 6.0 mm. in advance of the anterior pole whereas that corresponding to the 180° meridian section is but 2.2 mm. in advance of the anterior pole, and comprised within an axial line segment 3.8 mm. in length will be found all optical centers corresponding to the various meridian sections of the lens.

From the lens features alluded to in this article it must be obvious that the axial location of the optical center is dependent upon the characteristics of the lens design and it must be evident to the optical workman that his instrumentally determined point upon the lens surface is none other than the pole of the lens and not its optical center. Fortunately errors attributable to this misconception of lens characteristics have not been frequent since, prior to cutting the lens, the optical workman by means of a lens centering device locates and marks what to him is the optical center but which in reality is the lens axis and upon the latter, proper mounting of the lens in its frame is dependent. Were a judicious diaphragming of the lens system requisite to a proper correction of visual defects long ere this a comprehensive insight into the fundamental conceptions and laws pertaining to the position of the optical center of any optical system would have been demanded of all optical practitioners. The following tabulation states the position of the optical center of a few generally used ophthalmic lenses, the lens index being considered as 1.5, the notation in the above formula being adhered to fully.

Lens Power	Meniscus 6.0 D. Base		Meniscus 1.25 D. Base		$\sigma_1 = -\sigma_2$ Bispheric		Plano $\sigma_2 = \sigma$ Spheric	
	d	A_1O	d	A_1O	d	A_1O	d	A_1O
+2.00	3	—9.0 mm.	3	—1.8 mm.	3	+1.5 mm.	3	0
+4.00	3	—4.5 "	3	—0.9 "	3	+1.5 "	3	0
+6.00	3	—3.0 "	3	—0.2 "	3	+1.5 "	3	0
+8.00	3	—2.2 "	3	—0.15 "	3	+1.5 "	3	0
—2.00	2	+8.0 "	2	+3.2 "	2	+1.0 "	2	0
—4.00	2	+5.0 "	2	+2.6 "	2	+1.0 "	2	0
—6.00	2	+4.0 "	2	+2.4 "	2	+1.0 "	2	0
—8.00	2	+3.5 "	2	+2.3 "	2	+1.0 "	2	0

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Reflex Action and the Human Eye

Kenneth Shallcross Dickinson, F.C.S., Ph. C.

AT the very outset of this article, the writer would emphasize one outstanding principle; to wit: He is writing, not for the academic soul who is athirst for the very latest theory on some abstruse question of the ophthalmic autonomic system, but for the intelligent ophthalmic practitioner who has noted certain reflexes and reactions to stimuli in the course of his practice, and who may never have known, or may have forgotten with the years, the precise significance of them. At the same time, it is hoped that what is to be said may prove of use and interest to the advanced student also. If it is, then will the work have brought its own reward, in a sense of satisfaction to its author.

Let us, first, then, be sure in our own minds as to what we understand by the term *Reflex Action*. It may be summed up, briefly, thus:—"Reflex action is that response to a stimulus which is evoked independently of the will." Some reflexes are typical and well marked—as witness the "knee-jerk," the "pressure reflex" in the dog, and in the eye, the protective "eyelid reflex" whereby the lid is closed involuntarily on the approach of a foreign object to the cornea. There are, however, at the other end of the scale, reflexes which are almost obliterated by the modifying growth of civilization and habit. Such are typically seen in the inhibition by the higher centres of the reflex acts of micturition and defaecation, as seen in the civilized human adult. But some, lesser known and less studied, reflexes, which have undergone a certain amount of atrophy from disuse, occasionally give rise to queries and doubts in the minds of those whose work involves dealing with the human body. Some unexpected response to a given stimulus—some curious effect resulting from a cause which may or may not be known at the moment—these have from time to time given rise to much stimulation of grey matter, and oft-times to a certain heart-searching as to what was the cause, and hence the thought that a recapitulation of the connection of reflexes with the eye and its mechanism may prove acceptable to the readers of this *Journal.*

The essential structures, anatomically concerned in the production of a reflex movement, form what is known as a "Reflex Arc." The reflex arc consists of the following structures:—The sense organ, or sensory surface (skin, *e.g.*),

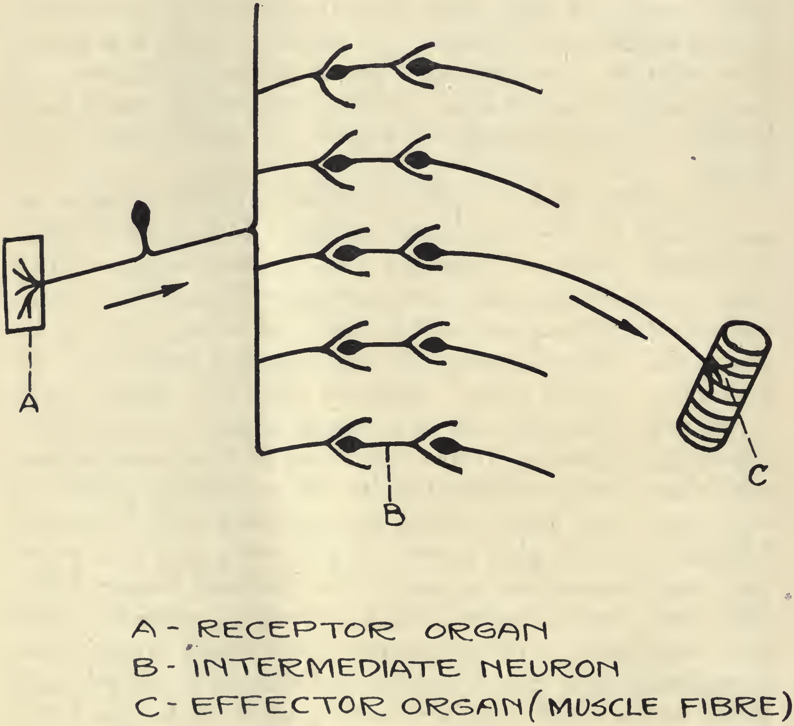

Fig. 1. Diagram illustrating a reflex arc.

an afferent nerve, a series of neurons in the nerve centre, an efferent nerve, and a muscle or gland. The point of origin of the impulse, *i.e.* the skin or sense organ, is usually known as the "Receptor" organ, and the muscle or gland responding to the impulse is styled the "Effector" organ. Functional power of the whole of this arc is essential if reflex action is to be maintained. (*Vide* Fig. 1.)

All reflexes may be primarily divided into two groups; those which cause the carrying out of some movement or groups of movement, and those which prevent the further carrying out of some movement. The latter type of reflex is styled an "Inhibitory reflex." More particularly, however, reflexes are divisible into three well-defined groups, according to the structures involved in their production. These are:—

Superficial reflexes; *e.g.* Scapular; Cremasteric
Deep or Tendon reflexes; *e.g.* Kneejerk
Organic reflexes; *e.g.* Pupil, Bladder, Rectum

The reader is earnestly invited to make himself or herself familiar with these reflexes mentioned in order to the more properly appreciate the differences in the causative factors. Newman Dorland's *Pocket Medical Dictionary* gives a very brief account, or better, a text on anatomy such as Gray's *Anatomy* gives such details as are essential to the purpose in hand.

So much for reflexes in general. What, next, is the actual anatomical reflex mechanism of the human eye? To commence with, it must be remembered that there is an extrinsic as well as an intrinsic nervous mechanism. The extrinsic mechanism may be very briefly dismissed, since it consists of identically the same nervous, receptor, and effector, mechanism as does any other part of the body reflex system. There are some movements which may almost be classed as "borderland" cases, since it would be difficult, if not impossible, to state definitely how far the action of the will entered into determination of the movement. Among such, for example, may be classed the movement of warding off or avoiding a blow directed toward the eyes. Probably reflex movement commences the effect, but almost certainly voluntary muscle response continues it to a degree far greater than any reflex movement is capable of doing. The movements originating within the eye itself are of quite a different category. For all practical purposes it will be permissible to group real or true reflex movements with those due to, or associated with, impulses from the autonomic nervous system, the results being difficult to discriminate between, although the causes are of obviously different origin. But our purpose is to outline the results and to deduce the practical conclusions where such may exist, rather than to spend too much time and space on prime causes, where these are abstruse or of secondary importance. The intrinsic nervous supply to the eye itself is derived from (1) the *optic nerve,* which is the nerve supplying the function of sight, and (2) the *ciliary ganglion.* This latter is made up of:—(A) Sympathetic fibres from the carotid plexus; (B) sensory fibres from the nasociliary branch of the ophthalmic division of the fifth nerve, and (C) motor fibres from the oculomotor or third nerve, from its branch to the inferior oblique muscle. Possibly there may be a delicate branch of communication from the sphenopalatine ganglion, situated in the pterygopalatine fossa. These are the roots of supply to the ciliary ganglion. Next let us consider the branches arising from this structure. These are the short ciliary nerves, and they are of the very utmost importance to the proper functioning of the organ of sight. So much so, indeed, that that part of the orbit affording lodgment to the ciliary ganglion is termed the "*Dangerous Area*" and wounds or pathological conditions in that district are regarded, and rightly, with a very serious mien. The short ciliary nerves number some six to ten, and are extremely delicate in structure, arising in two distinct bundles from the anterior aspect of the ganglion, (*vide* Fig. 2). The upper bundle runs above, and the lower bundle, which is the larger, below, the optic nerve, being accompanied by the long ciliary nerves, from the naso-ciliary, and being distributed to practically the same areas. Piercing the sclera around the optic nerve where it gains entrance, they are distributed to the cornea, the iris, and the ciliaris muscle. According to Tiedemann (to whom we owe much patient work on the anatomy of the eye), a delicate branch enters the optic nerve along with the arteria centralis retinae. That, then, constitutes the chief nervous mechanism of the eye. Summed up into its constituents, we find that the eye as a whole is supplied by nerve impulses from the second, third, fourth, fifth and sixth cranial nerves, and from the sympathetic system; that it has an important ganglion in close connection with it, the ciliary ganglion, and is possibly connected, nervously, with other aggregations of nerve elements in the skull.

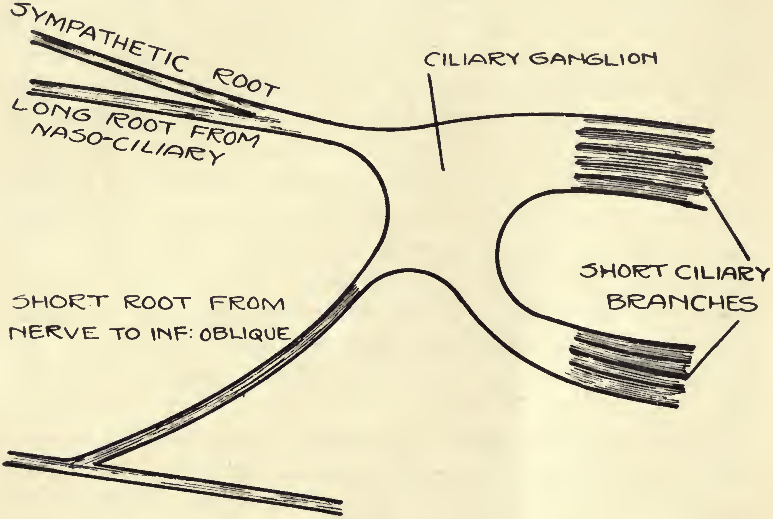
SYMPATHETIC ROOT
CILIARY GANGLION
LONG ROOT FROM NASO-CILIARY
SHORT CILIARY BRANCHES
SHORT ROOT FROM NERVE TO INF: OBLIQUE

Fig. 2. Plan of ciliary ganglion.

The reflexes shown by this mechanism, acting on the other structures of the organ may be, as already suggested, classified as extrinsic and intrinsic reflexes, according as to whether they are reflexes connected with the extra-bulbar or intra-bulbar mechanism. An alternative method of classification is to regard them as the products of either physiological or pathological causes; for it is well known that there are certain states of morbidity wherein these reflexes undergo profound alteration and variation, in some cases being entirely inhibited, and in others, being accentuated to an extremely high degree. Let us first consider some of the normal reflexes of the eye. First in order, comes the

Pupillary reflex, or *Miosis*. This is so familiar that more than a mere mention of it would be superfluous. We might just recall the cause, and the reason for the reflex. The cause—a marked increase of light. The effect—because this light must be shut off from the spread-out optic nerve, or retina, in all probability lest it should injure that still somewhat-mysterious substance, visual purple, or rhodopsin.

Eyelid closure. This is another constantly recurring reflex, needing only to be mentioned. Its function purely protective; it is called into play every time a foreign body approaches the conjunctiva. Also, and this is a point that is very frequently overlooked by the examination candidate, it materially assists in the moistening of the conjunctiva with lachrymal fluid, and therefore is called into play as and when the surface of the eye tends to become dry. It must be remembered in this connection that only a small proportion of the lachrymal fluid is disposed of by way of the lachrymal duct; the greater proportion disappears by evaporation from the exposed surface of the eyeball itself.

The *Ciliospinal* or *Platysmal reflex*. These have been separately described from time to time, but for all practical purposes may be regarded as one and the same. The reflex consists in a dilatation of the pupil on pinching the skin of the neck, or of the region especially, over the platysma. In any case, the general term of "the neck" covers the platysmal region, and as the stimulus and the result is exactly the same, it is only logical to group these two under the one head. This is a curious reflex and is still open to some surmise. Careful experiment shows that in the vast majority of cases, the reflex movement is not confined to the iris, but also spreads to the oculomotor nerve, causing a marked uplifting of the upper lid. That is to say, not only does the pupil within the eye dilate but also the structures surrounding the eye tend to open more widely also. What does this show? Most likely, in common with many other reflexes in man which seem of little use to him, it had an important bearing upon his survival in the dim past ages and it undoubtedly survives to a great degree in the lower animals today. By dilating the pupil it causes the admittance of more light, even if something of definition is sacrificed, and so a potential enemy may be the quicker recognized. This would be especially necessary if that enemy had already managed to get so near that a touch, or a hold, upon the neck or throat of the victim had been effected. This is a theory that is borne out by the fact that the same effect of dilation of the pupil is seen in undoubted cases of fright or shock (first stages), but whether the platysmal reflex first causes, through the sympathetic system, an output of adrenalin which in its turn causes this characteristic effect, or not, is still open to doubt. The rapidity with which effect follows cause would suggest that the dilatation of the pupil in the platysmal reflex is a direct effect of the stimulus and not an indirect one. However that may be, response denotes, so far as it goes, a healthy body, and a variation from this is of considerable diagnostic value.

Davidsohns reflex depends upon the stimulation of the optic nerve from an unusual direction. An electric light, held in the mouth, results in the seeing by the patient of an indefinite light at an apparently indefinite point before him.

The explanation here is fairly obvious. The light in the mouth penetrates the soft tissues, and entering the orbit through the pterygomaxillary and inferior orbital fissures, penetrates the bulb of the eye and so stimulates the retina. It is claimed that the stimulus may affect the optic nerve before it pierces the sclera, but the explanation given would appear to be the more reasonable. In this case, the reflex can hardly be a true reflex within the meaning of the term. It is, rather, an unusual method of effecting stimulation of the sensory nerve, after which the normal function of appreciation of light comes into play. Another, and true, reflex is the

Oculo-cardiac reflex, the essence of which is that the heart rhythm may be appreciably slowed on steady compression of the eyes. The slowing is of a variable degree in different patients, and would appear to be most marked in highly sensitive and young persons.

McCarthys reflex approaches very near to the eyelid closure reflex. It consists of a contraction of the orbicularis oculi muscle on tapping the region of the emergence of the supraorbital nerve. It is fair to presume that this is a natural protective response to what appears to be a nocuous stimulus, more or less vestigial in man, but markedly developed in the lower animals.

Let us briefly consider some of the deviations from the normal in these reflexes. Our space is limited, and the reader must simply be guided into the subject, and there induced to work out for himself those practical applications where opportunity offers, as indeed it does, in a greater proportion of cases than the average practitioner is aware of. In contradistinction to the normal pupillary reflex, or miosis, there may be met with

Bechterews reflex. This is sometimes referred to as the "Paradoxical pupillary reflex." Here, on exposing the pupil to light, it is seen to dilate still further, rather than contract. The same condition has been noted perhaps more fully by, and is described as, the *Argyll-Robertson* pupil, its technical name being

Reflex Iridoplegia. Here there is a failure to contract, or there may even be dilatation, on exposure to light, but contraction occurs in a normal manner on convergence or accommodation, and, whilst being perhaps somewhat more contracted in the resting stage than is usual, yet dilates readily on applying the ciliospinal or platysmal reflex stimulus. This is perhaps the most important of the ophthalmic reflexes, and has received much attention of late years.

With the methods of enquiry into these most interesting reactions it is hardly within the scope of this article to deal. The interested reader will find much that has bearing on the subject in any of the modern comprehensive text books on practical physiology, under the index heading of "Reflexometers," and "Reflexographs." Most of the apparatus in this domain has been devised to meet the special need of the particular worker, a statement which is perhaps true of most original sets of apparatus that are put together. But ample scope still exists for the eager and careful enquirer to improve the old, and to devise new, methods for the recording and interpretation of cause and effect in this branch of physiology.

On the uses of it all, much again might be written, did space and time permit. Suffice it to say that the uses are far-reaching and oft-times of vital importance. They may be regarded as falling under two main groups; *Natural* and *Deductive.* The natural uses are firstly, *Functional,* and secondly, *Protective.* The deductive uses are concerned as material with which to determine the vitality or disease of the patient concerned. Further analysis might be undertaken thus:—

Reflexes			
Natural		Deductive	
Functional	*Protective*	*Vitality*	*Disease*
Dilatation Miosis. Convergence etc.	McCarthys Eyelid closure. Ciliospinal (?) etc.	Reflex time of various natural reflexes.	Response to natural reflexes diminished or abolished. Reflex iridioplegia. Bechterews reflex, etc.

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Editorials

The Inversion of the Retinal Image

FROM time to time discussion arises as to the nature of retinal images—whether they are erect or inverted. In a recent paper Senet states that the retinal image is not inverted. Doubtless most, if not all, of the readers of these pages believe that retinal images are inverted. During the past year H. Hartridge (*Journal of Physiology*, October 19, 1920, and *Proceedings of Physiological Society*, May 15, 1920) has carried out some experiments on this subject of which the following is a brief summary:—

1 In the case of an ordinary animal the two outer coats of the eye may be removed with care from the eyeball leaving the retina in position. Observation of the retinal image shows that it is inverted and transposed.

2 If the eyeball of an albino animal is removed intact and mounted in a tube so that rays from an external object may enter the eye through the pupil only, it is then possible to examine the posterior surface of the eyeball and owing to the absence of pigment in the choroid the image formed upon the retina can be clearly seen. This image is found to be inverted and transposed.

3 The exit of the optical nerve lies to the nasal side of the fovea as we are taught by histological examination. The blind-spot (exit of the optical nerve) is found by experiment to lie to the temporal side of the point of fixation. It can be proved that the blind-spot corresponds to the papilla of the optical nerve by an independent observer A directing a beam of light with an ophthalmoscope into the eye of an observer B. It is found that if A directs the beam of light on to the blind-spot, B sees only a diffuse glow, whereas if A directs the beam anywhere else B at once clearly

sees it. And again, if the angle subtended at the eye by the blind-spot and the point of fixation is measured, it is found to be equal to that between the fovea and the center of the optic papilla as measured from the posterior nodal point. This would indicate that the retinal image is transposed in the human eye and therefore, since the optical system of the eye is a symmetrical one, there is an inverted image also.

4 Under certain pathologic conditions opacities formed in the eye media cast shadows on the retina. These are seen as projections on external objects and may be located by the perimeter or Bjerrum's curtain. It is found that opacities in one region or quarter of the eyeball cause regions of blindness which occupy the opposite region of the visual field.

5 By applying a powerful light stimulus or partially localized pressure on the exterior of the eyeball and as far from the summit of the cornea as possible, a projection of a glow is seen upon the images of the external object. This glow occupies the opposite portion of the visual field to that in which the stimulus has been applied.

Furthermore, it is obvious that if inverted images on the retina are re-inverted in spatial projections and are seen erect, then *shadows* of objects thrown on the retina, not being inverted, ought to become inverted in outward projection and be seen in this position in space. Le Conte (*Sight*, page 86) gives us a description of an experiment showing this. This phenomenon, he says, was first explained by him in 1871 (*Philosophical Magazine*, Volume LXI, 1871). The experiment is as follows:—Make a pin-hole in a card, and, holding the card at 4 or 5 inches distance—against the sky—before the right eye with the left eye shut, bring a pin-head very near to the open eye so that it touches the lashes: a perfect *inverted* image of the pin-head will be seen in the pin-hole. If, instead of one, we make several pin-holes, an inverted image of the pin-head will be seen in each pin-hole. The explanation given is as follows:—"If the pin were further away, say six inches or more, then light from the pin would be brought to focal points and produce an image on the retina; and this image, being inverted, would by projection be re-inverted and the pin would be seen in its real position. In the above experiment, however, the pin is much too near the retina to form an image. But nearness to the retinal screen is most favorable for casting a sharp shadow, and while retinal images are inverted, retinal shadows are erect. The light streaming through the pin-hole into the eye casts an erect shadow of the pin-head on the retina. This shadow is projected outward into space, and by the law of projection is inverted in the act of projection and therefore seen in this position in the pin-hole. It is further proved to be the outward projection of a retinal shadow by the fact that, by multiplying the pin-holes or sources of light, we multiply the shadows, precisely as shadows of an object in a room are multiplied by multiplying the lights in the room."

How, then, with inverted images do we see objects in their true position, *i.e.* erect? The answer is simply stated in what is known as the "law of visible direction or projection." This law may be stated thus:—When the rays from any radiant object strike the retina the impression is referred back along the ray-lines into the space and therefore to its proper position. A very simple experiment and a consideration of its significance demonstrate that the law of projection is the correct explanation. We know that objects appear in the same positions in space, *i.e.* vertical, whether these objects are viewed by a person standing erect or upon his head. For an object AB forms an inverted image B_1 A_1 upon the retina of the eye of the erect person; the image of A (upper portion of object) is formed upon the lower portion of the retina at A_1 and is projected outward through the nodal point to give the point A its proper position in the upper portion of the object. When the eye is inverted, as is the case when a person is standing upon the head instead of the feet, then the object AB again forms an inverted image B_1 A_1, but the image of A (upper portion of object) is formed upon the lower portion of the inverted eye—which corresponds to the upper portion of the retina of the erect eye—at A_1 and is projected outward and upward to give the point A its position in the upper portion of the object. In either case—with head erect or inverted—objects are seen correctly in space, whereas the image formations upon the retina are exactly reversed in so far as their anatomical locations with respect to the fovea are concerned. In the case considered the image of A, with head erect, is formed retinally in the lower quadrant of the eye; with head inverted the image is formed upon that which would be designated anatomically as the upper half of the retina of the erect eye. We have every reason to believe that this simple test proves the existence of inverted retinal images and the adequacy of the law of projection to explain the phenomenon of erect vision, and that an analysis of this experience leads to the conclusion that if retinal images were not inverted we should have an inversion of objects in space with inversion of head and eyes—unless perchance there is some "flip-flop" mechanism of which we know nothing.

Corresponding or Identical Retinal Points

THIS doctrine as it is commonly accepted and stated in treatises on various phases of physiological optics may be briefly expressed as follows: Objects are seen single where their retinal images fall on corresponding or identical retinal points. If the image of a given point is located at the temporal side of the macula of the right eye, the impression should also be located at the nasal side of the macula of the left eye and at a distance from it equal to that of the impression of the right eye from the macula if the points are corresponding and singleness of vision is to occur. Likewise, if the image is impressed at an horizon above that which passes through the maculae or below that horizon, then the impression for each eye must be equally above or below this horizon. These points are, therefore, not anatomically but rather geometrically similar, for simple constructions and considerations show that the corresponding retinal images are in entirely different localities anatomically. They are not only equally removed from the maculae but they also lie on corresponding horizontal meridians of the two retinae. Hence we may say that a point on one retina corresponds or is identical with a point on the other one when the images of the same exterior point, falling on the two retinal points, are seen as a single image. If, on the other hand, the image is formed on any other point, it is not blended with that of the first eye and the point is seen double. Helmholtz stated the law of corresponding points as follows: "Upon the *apparently* vertical concordant lines of the two eyes, points which are at equal distances from the horizontal meridians are corresponding points," and "Points which in the retinal horizons are at equal distances from the point of fixation are corresponding points." With respect to corresponding points in the field of vision he says:—"Corresponding points in the two visual fields are those which are at equal distances and equal in direction from the corresponding horizontal and apparently vertical meridians."

Stevens has criticized these statements of Helmholtz and holds that the propositions are inconsistent with the illustrations given and states that one of the most conclusive proofs that retinal corresponding points are not at geometrically equal distances in the two retinae is that a straight line drawn in the vertical or horizontal direction does not appear curved as it would positively do were the accepted doctrine correct. There is a mental cognizance of relations of distances in space and distances on the retinal surfaces, but they are recognitions of angular rather than of equally removed spatial values on the two retinae. Stevens, then, sums up his conclusions respecting this subject in the following statement: "Corresponding points are those points in the retinas which answer to proportionate degrees of rotations of the eyes about their centers of rotation and which, from given points in the plane of the point of fixation, receive incident rays which must pass through the nodal points."

The question arose, after the propounding of the doctrine of corresponding points of the retinae and of identical spatical points of the two fields of view, as to whether the property was innate, instinctive, and antecedent to experience, or was wholly the result of experience. This question has long been discussed by various thinkers; the former view was held by Müller, Pictet and others and the latter view by Helmholtz, Brücke, Prévost and Giraud-Teulon. The one is called the *nativistic* and the other the *empiristic* theory. It is entirely possible that both are in a degree true and therefore not wholly inconsistent with each other.

There are, therefore, two adjustments of the eyes in every act of binocular single vision, viz., *focal* and *axial*. In the former, each eye is adjusted by the ciliary muscle to make a perfect image on the retina: in the latter, the two eyes are turned by the recti muscles so that their axes shall meet on the point of sight. The one is, therefore, an adjustment for *distinct* vision, the other for *single* vision. Hence there are two great and fundamental laws by which all visual phenomena are expressed, viz.: (1) the law of direction and (2) the law of corresponding points; both may, in fact, be called laws of corresponding points. The one gives the true position of all points in space—the theory of projections; the other expresses the anomaly of single vision with two retinal images. The one affirms the correspondence, point for point, of retinal rods and cones with external space, with ray-lines connecting and crossing in the nodal point. The other asserts a correspondence, point for point, of the rods and cones of the two retinae. From the one, therefore, follow all the phenomena of monocular vision and from the other all the phenomena of binocular vision.

The Progress of Visual Science in 1920

Leonard Thompson Troland, Ph. D.

Foreword

IT is the purpose of this annual summary to assemble and to abstract briefly all original papers, having a sufficiently important bearing upon visual science, appearing during the given year in English, French or German. Papers in other languages which have been abstracted elsewhere in any of the three mentioned languages will also be included. All physical, biological, and psychological publications which are accessible to the reviewer will be examined. Ophthalmological literature will be searched for contributions of general scientific significance in this field, but it would of course be impracticable as well as supererogatory to cover the entire province of ocular or visual pathology. The reviewer's conception of the utility of this annual summary is based upon its function of gathering together actually homogeneous material from sources originally widely scattered. There is probably no topic except vision, which can find a legitimate place in so many different publications. Other extant summaries and abstracts seem to be confined to specialized collections of sources. The provinciality and redundancy of a great deal of the literature on vision reflects this constant lack of centralization of ideas. The task of remedying this condition is necessarily a difficult one, and the present reviewer makes no claim either to absolute completeness in his list of references or to perfect accuracy in his abstracts. Deficiencies in these respects nevertheless represent departures from his ideal, and he will therefore be indebted to any reader who will indicate desirable additions or corrections. Such information, together with tardy data discovered by the reviewer himself, will be utilized in supplementary summaries to be published as the occasion warrants.

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I Introduction

The discussions of visual problems which appeared during 1920 seemingly exceed in number those of any previous year. Contributions stimulated by the tasks of the War are still in evidence, but the greater mass of the literature has a purely scientific or a peace-time significance. The question of the visibility of radiation, which has been so much to the fore in recent years has received less attention, but colorimetric problems have been attacked vigorously by many workers. Several new colorimeters have been described and analyses of such color systems as those of Munsell and of Ostwald have been carried out with great thoroughness. Advances have been made in methods of measuring visual acuity and thus in the detection of errors of refraction. Several careful studies of oculomotor processes and of certain entoptic phenomena have appeared, in addition to anatomical researches on the eyes of man and of lower animals. New tests have been made upon the influence of illumination conditions upon the eye. Hecht has made important initial contributions in a new study of the chemistry of the visual purple, and Ferree and Rand have continued their very careful measurements on the retinal color fields. Color blindness has received considerable attention, special emphasis being laid upon methods of testing. Schjelderup and several other writers have demonstrated a marked influence of contrast conditions upon Weber's law in vision. Rates of rise and fall of sensation and flicker have been studied further, the work of Bills on the growth curves for chromatic stimuli and of Piéron on the absolute light threshold as a function of exposure time, being of particular interest. Sheppard and also Juhász have made extensive experiments on chromatic adaptation. New discussions of the theory of vision are numerous, that of Schjelderup being the most suggestive. Several unfamiliar phenomena due to central disorders of the visual apparatus have been described in great detail, and a large group of studies on visual perception and allied topics have appeared. The problems of the apparent sizes of heavenly bodies and the mathematics of visual space have been much debated by Teutonic investigators. Finally, many contributions have been made to our knowledge of photic response in lower animals. Hecht has continued his analysis of the receptor process in certain molluscs, and the indefatigable von Hess has offered new accounts of reactions to light in many invertebrates.

II Photometric Considerations

A number of very comprehensive and accurate summaries of the visual factors involved in photometric and allied problems appeared during the year 1920. Nutting has presented four new reviews of his valuable collection of data on this subject. One (133) takes the form of a discussion of the optical principles of illuminating engineering, dealing with conditions for best seeing, brightness and retinal flux densities, together with the lower and upper limits of vision. The second (136) consists of the annual report of the Standards Committee on Photometry and Illumination of the Optical Society of America. This report summarizes the units and nomenclature of photometry, as well as standard photo-visual relations, including visibility values, brightness sensibility data, glare limits, etc. The third (135) considers these and other closely related facts, from a more physiological point of view, as illustrating the reactions of the retina to light. The fourth (134), comprising the Report of the Committee on Visual Sensitometry of the Optical Society, covers similar ground. These last two papers consider chromatic as well as achromatic sensibility, also rates of adaptation and absolute sensibility. Many very valuable tables and graphs are presented. In the fourth there is an especially complete summary of absolute threshold data, with its dependency on time and area; and useful evaluations of retinal flux densities under various conditions. The major part of the contents of these papers has been published previously, and hence they will not be analyzed in detail here. Reeves (157a) offers a brief summary of the fundamental principles of visual sensitometry based mainly upon investigations at the Eastman laboratory. The paper deals with the brightness discrimination function, the ranges and rates of adaptation, absolute visual thresholds, the visibility curve, glare limits, pupillary responses, hue sensibility, and other related topics. All of the fundamental data have been published previously elsewhere. In the discussion of this paper Edridge-Green takes exception to the statement that 128 distinct hues can be discriminated in the spectrum, his experience being that the ordinary person can only distinguish about 18 different hues. It was the general opinion that the difference between these two sets of results was attributable to the absence of a clear set line of demarcation between the compared fields in the case of Edridge-Green's experiments.

Piéron (144) has prepared a lengthy discussion of "the physiological principles which should govern all studies of light." Facts bearing on the problem are grouped in support of seven specific principles, from each of which practical consequences are deduced and all of which justify the single general principle that light is not an objective or physical entity, but an effect producible only through the physiological reactions of an organism. Original contributions of data by the author are limited to the problem of the laws of temporal and spatial summation of liminal stimuli, but these have already been published elsewhere. (A detailed analysis of the paper, by the present reviewer, will be found in the *Transactions of the Illuminating Engineering Society*, Volume 16, pages 44 - 50.)

Jones (100) supports the thesis that the concept of *brightness*, which is fundamental to illuminating engineering, can only be defined in terms of visual sensation. His argument summarizes and employs established data regarding visibility, summation of brightnesses, the brightness values of the elementary color sensations, etc., and leads to revised definitions of photometric concepts. Objective brightness and the intensity of visual sensation are regarded finally as being substantially identical. So (173) has discussed the visibility of radiation throughout the spectrum, in a paper not at present available to the reviewer. Ferree and Rand (53) take exception to the reviewer's treatment of their paper on visibility functions, in his annual summary, indicating data from which their field areas are to be determined and further defending their results. The reviewer (181), in a rejoinder, endeavors to justify his original criticisms and points out further important omissions in the description of experimental technique which make it difficult to interpret the changes in the form of the visibility curve, with intensity, demonstrated by these investigators. Computation of the retinal illumination values for these and other investigations indicates either that the field-sizes used were too large or that data upon which standard visibility values are based lie in the region of the Purkinje effect. The reverse Purkinje effect shown by one of Ferree and Rand's series may be an artifact due to the pupillary arrangement which they employed.

Richtmyer and Crittenden (158) find, by analysis of a large amount of photometric data taken under conditions maximally favorable to precision, that the average deviation for a single match may be as low as 0.314 per cent., when there is no color difference. A slight color discrepancy, corresponding to a temperature difference of 20 - 35° in a light source, raises the value to 0.38 - 0.40 per cent. The Lummer-Brodhun contrast photometer was employed. Precision decreases very rapidly with increasing color difference, and settings lose reproducibility. For considerable color differences, such as that between light from the carbon and gas-filled tungsten lamps, the flicker-photometer shows marked superiority, with its substantially constant precision of 0.75 per cent.

Karrer and Tyndall (107), in connection with practical problems of searchlight illumination, have determined the relation between the brightness discrimination threshold and the size of the test object under various conditions. The object took the form of a strip of variable length. In one series of measurements, a constant background was employed, with alteration in the brightness of the object only; while in another series the ratio between the background and the object was constant, but the absolute intensity of both was varied. The conditions are specified quantitatively and the results are tabulated in full.

Jones (101) has utilized the established contrast sensibility curve of the eye, with data for different adaptation levels, as links in a complex chain of reasoning concerning the faithfulness with which a photographic positive can reproduce the luminosity values of the original scene to the eye. He divides this problem into the subjective and the objective phases, the former being visual and the latter purely photographic.

III Colorimetry, Color Mixture, and Allied Problems

Priest (154) reports elaborate studies of the leucoscope, a much neglected instrument, which provides a ready means for approximately duplicating the various spectral distributions of energy, characterizing common illuminants. The central feature of this paper lies in the application of the instrument to pyrometry, but some of the elements of its visual theory, in particular the personal equation, are discussed, and the determinations of the "color temperature" of daylight at various hours between sunrise and sunset by means of the instrument are of particular interest to the student of vision. The curve representing this temperature as a function of the time of day is roughly half of an ellipse, with its major axis parallel to the time line, rising from a minimum of approximately 2000° to a maximum of 5400°. Very complete calibration data for use of the instrument are presented.

Jones (103) describes a colorimeter, operating on the subtractive principle, in which green, blue, red, and neutral gelatine wedges are employed in superposition, permitting color-matching of practically any object. Calibration curves of the wedges and details of design and application of the instrument are provided. The permanence of the dyes employed in the wedges has been insured, and although the instrument is primarily intended for field work, attachments have been designed for measuring small samples of transmission or reflection colors. Hartridge (67) discusses the various factors entering into the design of a visually satisfactory chemical colorimeter. He believes that the general optical design should correspond to practice in the case of microscopes. The best comparison field, nature of the artificial light source, and the use of filters to increase accuracy, are considered.

Pfund (143) has designed a special colorimeter for detecting and measuring small deviations of reflection colors from a pure white, a device much needed in paper, textile and paint industries. The small chromatic factor is accentuated by the use of several successive reflections of light from the type of surface to be measured. The application of the instrument shows that even the standard non-selective surfaces, magnesium oxide and carbonate, are not perfectly white; monochromatic color analyses of several supposedly white surfaces being given.

Coblentz (17) presents in full his revision of data on the energy distribution of the cylindrical acetylene flame, in the spectrum. Radiometric, as well as color temperature measurements, indicate that between 480 and 740 mμ the distribution is that of a black body at 2360° K. The revision of data for the violet end has no effect on previously published visibility values in which the acetylene flame characteristics were involved. An approved table of visibility values is appended. Hyde and Forsythe (94) find that the method of comparing the energy distributions of common light sources by color-matching does not always determine exactly the same spectral distribution. When the light from an untreated carbon filament is color-matched with a black body, the distributions are substantially identical, but tungsten differs from a black body by 0.5 per cent. at 1500° and by 8.0 per cent. at 2900° K. Tantalum shows a 6.0 per cent. deviation throughout approximately the same temperature range.

Priest (151) announces the existence of a preliminary draft of the Committee on Colorimetry of the Optical Society of America, a copy of which can be borrowed by mail from the Library of the Bureau of Standards at Washington. This report deals in detail with general color terminology, outlines the various methods of colorimetry, terms related to transmission and to monochromatic analysis, and also considers standards of spectral energy distribution, transmission and reflection—all of which are important.

Ferree, Rand, and Haupt (55) have developed means for maintaining the daylight color of a room for optical research constant. A tungsten lamp combined with various filters is taken as a standard, and a photometer arrangement permits comparison of this with the light of the room. Various types of photometer head, and various filters, as well as colored papers, at different intensities have been tested for sensibility, in terms of the voltage change of the lamp required to yield a threshold color difference. The best results were obtained with the Lummer-Brodhun head, at high intensities and with daylight color. The approved apparatus permits simultaneous standardization of the intensity and color of the room illumination. Bluish lamps are to be used to correct the natural color variations. Boring (9) describes an extremely inexpensive protractor for measuring the sector angles found in color-mixture experiments with disks. He also reports that artificial daylight lamps (Mazda C2) have been found superior to uncontrolled daylight for color-mixture work in his laboratory. Martin (123) has exhibited a new type (Sheringham) daylight lamp, a British product, at a meeting of the British Illuminating Engineering Society. Hartridge (69) outlines a technique for the rapid production of color filters. Garten (59) describes in detail, with drawings and photographs, the elaborate spectral color-mixture apparatus which was used by Hering for thirty years, but was never described by its originator. The arrangement consists of three spectrometer elements, the rays from two of which are mixed on one side of a comparison field, those from the other filling the opposite side of the field. All of the light from the field is concentrated upon the pupil by a magnifying telescope system. Variation of the wave-lengths is accomplished by motion of the collimating elements, and a double slit attachment is also provided. The entire set-up is worthy of careful study by workers in this domain.

Priest, Gibson, and McNicholas (155) have made a spectrophotometric study of the Munsell Color System, and present spectral reflection curves of representative Munsell grays and chromatic colors. The Munsell "value scale" is found to be proportional to the square-root of the light reflecting power of the graded colors rather than directly proportional, as intended: a condition which is, however, preferable to the intended one, although a logarithmic relation would be a still further improvement. Other suggestions for the standardization of the system are offered. Kohlrausch has carried out a similar, very careful, analysis of Ostwald's new color system, as represented by the pigments in three color-circles given in his color atlas. Kohlrausch defends the merits of the Young-Helmholtz analysis as a method of specifying colors, and somewhat deprecates the Ostwaldian substitutes. Incidentally, he makes some valuable contributions to general color theory, besides offering concrete demonstrations of the applications of three-color analysis. In his first paper (111) he presents complete data on the reflection coefficients of the Ostwald pigments throughout the spectrum, and by combining these with solar energy distribution and König's three elementary color sensation curves, he deduces the three-color sensory values for each of the pigments. These values are plotted in the color triangle, forming irregular ellipses, with their long axes roughly parallel to the yellow-to-violet range of the spectral locus. From them, the dominant hues and saturations (or cancellation ratios) are computed. Experimental measurements of these two characteristics were also made and, as plotted, agree well with the theoretically determined values. The method is adequately described. The second paper (112) deals with the brightness aspect of the mooted pigments. By use of a "cascade" method of photometric comparison of the different colors, Kohlrausch arrives at values of 0.683 : 0.422 : 0.027 for the coefficients by which the red, green, and blue sensations, respectively, must be multiplied to permit their addition as luminosities. By means of these coefficients, based upon twenty-four separate intercomparisons for the writer's eye, luminosity values for the Ostwald pigments are computed from the previously obtained sensation values. The coefficients are also applied to the original König sensation curves, and are found to yield a spectral luminosity curve agreeing well with Exner's empirical findings on the long-wave side, but departing considerably from the latter in the center and in the short-wave end of the spectrum. In his third paper (113) Kohlrausch criticizes Ostwald's method of specifying pigment colors in terms of color plus black plus white content. This scheme may be helpful in practical work, but cannot be regarded as representing an advance in the science of color, and on account of its very poorly fulfilled assumptions concerning the form of the spectral reflection function and its conflict with experience, is not fitted to replace the Young-Helmholtz analysis. Moreover, it brings about a false separation of pigment from radiation colors. The argument is supported throughout by concrete applications. Meissner (124) also reports measurements on some of Ostwald's filters and reflection colors, continuing his previous publications on similar topics. He considers in particular the gray scale and the saturations of the colors in the 24-part circle of the *Farbenfibel.* Some of the pigments are satisfactory, while others need improvement. Incidentally, he notes an apparent independence of the mean error of his measurements on the gray scale, of the brightness; but the total range of intensities as well as the precision of the data scarcely warrant their application in a criticism of Weber's law. In another paper (125) the same writer gives data on the colors of vegetation at different times during the summer, and on differences in the colors of leaves depending upon reflection factors, appearing between daylight and gaslight measurements. Prange (150) reviews four of Ostwald's recent

(1919) contributions to the literature or science of color.

Schrödinger (167) outlines the theory of pigments having maximal light intensity. Jones and Reeves (104, 105) discuss, for the benefit of psychologists, the various principles involved in the exact specification of chromatic stimuli. Radiation must be treated by analytical, sensation by synthetic, methods. In addition to a consideration of general spectrophotometric concepts—including those of selective reflection and transmission—the relation of the visibility curve to spectral luminosity curves, the principles of monochromatic colorimetry and the hue and saturation scales, are sketched briefly.

Dimmick (26) presents experimental evidence to show that the relation of the black-to-white series of qualities bears the same relation to mid-gray as does any given chromatic complementary series, such as the blue-to-yellow. Subjects picked out the same gray as median from an achromatic series as from a chromatic one, and with equal precision. By thus assimilating the gray series with the various chromatic series, the color solid becomes dimensionally homogeneous about the mid-gray as a nucleus, all departures therefrom being expressible in terms of the *saturation* of some characteristic factor, among which white and black rank coördinately with red, yellow, green or blue.

Schrödinger has developed a profound mathematical analysis of some fundamental questions of color measurement, with reference particularly to the definition of heterochromatic brightness.

Priest (153) finds that if the data for the wave-lengths of complementary colors, as given by Helmholtz, are reduced to frequencies, their graphical representation is much more closely similar to a rectangular hyperbola than when the same data are plotted as wave-lengths. The equation for the curve is

$$(530 - f)\ (f_{\text{comp}} - 608) = 220$$

where the frequencies are in Fresnels, f_{comp} representing the frequency of the complementary to *f*. Incidentally the writer makes certain suggestions for measurements to be made concomitantly with a new determination of the visibility function. The same author (152) finds experimentally that the centers of gravity of the spectral distributions of luminosity for any two stimuli yielding the same color are coincident. This conclusion is based upon spectrophotometric data for a wide variety of stimuli, including so-called monochromatic analysis results as well as measurements on pigments, etc. Any inaccuracies in the relation can be accounted for in terms of the color discrimination threshold. The data are presented in the form of graphs and the method of computation is described in detail. The converse of the proposition established by these experiments is not necessarily true, a further condition being required.

Hillebrand (86) replies at great length to F. Exner's criticism of his work relating the Purkinje phenomenon to the specific brightness of colors. As a corrective of Exner's confusion of the subjective and objective visual contrast the writer reviews the definitions of these fundamental ideas as used in the Hering theory. The physical and the psychological concepts must be kept strictly separate. The problem of the specific brightness of colors arises from the question as to whether the different colors considered as divorced from white or gray are of the same or different brightnesses. The doctrine of different specific brightnesses which is characteristic of the Hering theory implies that brightness is not independent of hue. The relationship between the two is made clear by means of triangles. The Purkinje effect demands a change in the state of adaptation as well as in the stimulus intensity, and is accompanied by a change not only in the relative brightnesses of the compared colors but also in their relative saturation. The most significant way of studying the Purkinje effect is to equate in brightness the various stimuli to be compared, at a low intensity and with dark adaptation, and then to increase the intensity. It will be found that this change causes red and yellow to become relatively brighter than a neutral gray whereas green and blue become relatively darker. This difference is in the same sense as the doctrine of the specific brightness of colors in the Hering theory. However no immediate deduction as to the specific brightnesses of colors can be made from observations on the Purkinje phenomenon on account of the fact that the white valences of the various colors may change unequally in this effect. For this reason it is necessary to work with pairs of colors which have constant white valences at all intensities. The writer then proceeds to show that in experiments previously reported by him in which these conditions were realized in the comparison between a chromatic and an achromatic stimulus an alteration in the relative intensities of the two was produced by a change in the intensity or adaptation level. This change could not be attributed to a change in the relative white valences of the two colors, and hence must be accounted for on the doctrine of the specific brightness of color. A detailed analysis of Exner's own experiments bearing upon the problem of the specific brightness of colors appears to demonstrate a lack of understanding of the problem on his part.

IV Visual Acuity and Accommodation

Southall (174) offers an extremely helpful mathematical analysis, with many diagrams, of the refraction characteristics of the human eye. After considering the general nature of the eye as an optical instrument, he treats in details the following questions: the positions of the cardinal points, the refractive power —stationary and dynamic— of the eye, the image equations, the apparent size of the object and its connection with the size of the retinal image, the size of the retinal image of an object seen through spectacle glasses, the resolving power and visual acuity of the eye, the relative visual acuity with spectacle glasses, indistinct vision, focus depth and accommodation, and the manifest amplitude of accommodation. Kirsch (109) reports the results of tests of a new acuity object, made by the Zeiss firm, in which a virtual image can be continuously varied in size without accompanying alteration of its distance from the observer's eye. Letters and Landoldt rings were employed as objects and the instrument was found to be very satisfactory. The writer also analyzes the concepts of "absolute, natural, and relative visual acuity." Lohlein, Richter and Schwartz (120) have determined the best test-objects for ascertaining the visual acuity of children too young to read, paying particular attention to the psychological factors involved. They find that the best consistency is obtained with representations of objects the nature of which is independent of absolute size, and that three-dimensional objects are not superior to drawings in black on a white ground. The use of colors interests the child in his task. Objects must be selected which are well known to the particular child to be examined, and must have characteristic outlines. Those are chosen which show the smallest variability in result for the emmetropic eye, and the relative sizes of different objects must be decided by experiment. Ewing (40) recapitulates the history of visual test-objects for the illiterate.

Hess (77) finds that a reduction in the acuity of the normal fovea amounting to more than 50 per cent. can be brought about by the action of one or two drops of 2 per cent. pilocarpin or eserin, the effect being shown to be retinal by the failure of spectacle lenses to remedy it. It persists as long as two hours, and is accompanied by entoptic visibility of the yellow spot and fovea, as well as by suppression of the entoptic representation of the blood vessels immediately surrounding the fovea. It may be due to an effect of the miotic on the tonus of the retinal vessels.

Ferree and Rand (42, 43, 44) describe a lantern for the controlled illumination of acuity test charts, and for the clinical determination of various threshold functions. As applied to acuity tests, an iris diaphragm is used to produce a continuously regulable known intensity, with practically perfect uniformity over the entire area of the chart. Although primarily intended for testing acuity at low illuminations, the apparatus has a wide variety of applications, both in the clinic and in the laboratory. The introduction of neutral filters, or Nicol prisms (45), permits reduction of the illumination to a point where absolute thresholds and rates of dark adaptation can be determined. Color filters convert it into a device for testing the color sense. One of its most important applications lies in the detection of small errors in refraction, particularly astigmatism, which become more apparent at low than at high illuminations. The writers report (46, 54, in collaboration with Buckley) results of an extensive study of this latter application, in conjunction with studies concerning the influence of dark adaptation on acuity. They find that 45 minutes dark adaptation considerably decreases the difference in acuity between different individuals, as measured by the minimum illumination required to recognize the test object. By this same criterion, the two eyes of the same subject were found always to differ, and in 88 per cent. of the cases the binocular threshold was lower than the monocular. The minimum illumination decreases asymptotically in the course of dark adaptation, showing little change after fifteen minutes. Twenty-two observers were employed and the results are relevant to the ocular requirements of the lookout and signal service of the navy. In its application to the detection of refractive errors, and the determination of the proper strength and placement of cylinders to correct astigmatism (47), the method is found to have remarkable sensitivity. Howard (92) describes a new apparatus for determining the near-point of accommodation, which reduces the uncertainty of this determination by compelling a uniform method and an objective criterion. It consists of a Prince rule combined with a card or disk bearing small interchangeable letters.

Hyde, Cobb, Johnson, and Weniger (93) have made elaborate tests, for the military service, of the relative merits of binocular and monocular field-glasses. Field tests with a small number of practiced observers indicate that the former give no better results than the latter when used with the observer's better eye. Laboratory tests show slightly superior results with the binocular glasses under conditions of twilight vision. Field tests with a large number of unpracticed observers show a slight balance in favor of the binocular glass, which, however, would be completely offset by an increase of 4.5 per cent. in the magnifying power of the monocular glass.

Kletzky (110) discusses the law which connects the reflexes of convergence and accommodation. He notes that convergence starts not from a state of parallelism of the two lines of sight but from a condition of slight divergence, and maintains that a similarly negative starting point exists in the case of accommodation, a slight degree of contraction of the ciliary muscles being required to focus the eye on infinity. He adduces evidence that even in myopia a constant tonicity of these muscles exists, and his thesis is that efficient binocular vision demands an undisturbed synergism of binocular adjustments throughout their entire range.

Feilchenfeld (41) has collected data on the near-point of accommodation for 7254 German people since the War, and estimates that half of the inhabitants of Germany older than thirty years have a markedly reduced power of accommodation resulting from premature senile involution, an outcome of war conditions.

French (57) reports very accurate and careful measurements of the precision obtainable in setting two lines to apparent coincidence. His apparatus was arranged to represent the conditions obtaining in many standard measuring instruments, such as the vernier. The average of a large number of determinations yield the astonishing precision of 0.58 seconds of visual angle. Tests were made on the influence of various factors upon the precision. Below an angular height of about 6.0 minutes the precision decreases rapidly with decrease in height of the coincident lines. At a lower limit of about 0.6 minutes the precision fails almost completely. The precision is greater for narrow than for broad lines and decreases with increase in the width of the zone separating the two lines which are to be brought into coincidence. The laws representing the complex interrelation of these factors are indicated by graphs. The deviation of the settings from the absolutely correct position was often greater than their variability, a fact which appears to be correlated with the verticalizing power of the eye. Experiments on this power show that in the case of one observer verticalization was accurate to about 40 minutes for a line of considerable length. Astigmatism probably plays an important part in aberrations of this faculty.

V Ocular Structures and Mechanisms; Entoptic Phenomena

Meyer (126) has studied the structure of the crystalline lens in 102 living individuals, and finds that at all ages there are detectable ten separate layers, between which discontinuous variations in refractive index occur. He describes the morphology of these layers at different ages. His findings oppose the theory of a continuous gradation of optical density from the surface to the nucleus of the lens. Senet (170) endeavors to prove that the image on the retina is not inverted. He maintains that the parabolic form of the posterior surface of the lens, combined with refraction occurring at the boundary of the vitreous humour, compensates for the tendency of the anterior portion of the refractive system to invert the image. Hartridge (68) replies to this palpably erroneous doctrine, by pointing out some of the very reliable evidence upon which the idea of the image inversion rests. In addition to general optical reasoning, actual observation of the images formed in enucleated eyes, as well as the relations between various entoptic effects and visually perceived objects, demonstrate the inversion beyond peradventure.

Reeves (157), using six subjects, has determined the size of the pupil in equilibrium with different brightnesses over a wide brightness range. With both eyes open, the size is practically constant between 10^{-6} and 10^{-2} millilamberts. The effect of closing one eye, upon the pupil of the other eye, is considerable over almost the entire intensity range. Tables and curves are given showing the diameters between zero and 2000 millilamberts, the extremes being 2.0 and 8.0 mm. The writer has also made measurements by means of a motion picture technique of the rate of closing of the pupil, finding the maximum constriction to be reached in 4.5 seconds, the greater part of the change occurring in two seconds according to an asymptotic curve. Measurements of the rate of opening show that it takes as many minutes for this process to occur as it does seconds for the closing, the maximum dilation being reached in three minutes. The brightness changes in these measurements were between total darkness and 100 millilamberts. Byrne (12) discusses the paradoxical pupil dilation which is observed in connection with certain cases of afferent path lesions, and finds indications that it is due to the activity of the smaller neuron bodies of the dorsal root ganglia, the efferent impulses being derived from afferent currents arriving at the upper thoracic segments.

Koby (115) describes various features of the fundus of the eye, as seen by red-free light with the ophthalmoscope. With long-wave light the retina appears to be transparent and with very little reflex but with short-wave illumination it seems opaque and exhibits a strong reflex. The red-free light reveals the macula lutea very clearly as a yellow area in contrast with the general green, thus affording evidence that this structure is not a post-mortem artifact. The courses of the retinal nerve fibres can also be made out clearly. A colored plate is given, depicting the appearance of the retina under the minus red illumination.

Dewey (24) has studied the distribution of lymph channels and capillaries in different portions of the eye, finding these to be absent from the cornea, the retina, and the tarsal cartilage, although most of the other parts are well supplied. Bonnefon (8) discusses the origin and regulation of the intra-ocular pressure, taking issue with Magitot's doctrine that the uvea is an erectile organ. He divides the circulation of the eye into two contrasted systems, those of the choroid and of the ciliary regions, respectively, the latter being responsible for the ocular tonus. Hiwatari (88) notes that the Japanese commonly show a strong pigmentation of the epithelial and sub-epithelial tissues of the conjunctiva, and that this increases with age.

Buys (10, 11), and Hautant (70), have made careful studies of normal nystagmus. Buys, using a rotating armchair, has determined the effects of known accelerations between 0.8 and 81. degrees per second. Nystagmus appears with accelerations less than one degree and its magnitude increases with increase in the intensity and duration of the acceleration. The sensation of turning is not clearly aroused until accelerations in the neighborhood of two degrees are reached. The intensity and duration of the nystagmus (11) depend not only upon those of the stimulus but upon a further factor representing the resultant effect of previous stimuli, which may have been contra-effective. This factor primarily influences the duration, while the intensity of the immediate stimulus mainly determines that of the nystagmus. Hence the intensity and duration of the latter are not necessarily proportional. Hautant discusses the nature of nystagmus and then describes in detail various methods for setting off the nystagmic reflex: thermal, gyratory, galvanic, and pneumatic procedures. The normal and pathological responses are analyzed, and the theory of the nerve connections involved is carefully considered. Lafon (116) writes on nystagmus at great length, but mainly from the standpoint of pathology. His classification and analysis of various forms of the disorder and his presentation of the theories which have been advanced to explain them will be of interest to the specialist. Stassen (175) has studied the causes of nystagmus in miners, which lie in general in the great visual effort required for work in semi-darkness. Incidentally, he classifies the oculomotor responses.

Ohm (137) concludes from his observations that there is a constant tonus of the external eye-muscles which is maintained by impulses derived from the vestibular and optic nerves. The trigeminal and auditory channels probably also make contributions. Bartels (3) hopes that many unsolved problems concerning the mechanisms underlying eye-movements in man may be illuminated by a study of these reactions in lower animals. Reviewing our knowledge of this subject, he divides eye-movements into the following classes: photic, vestibular, peripheral-sensory, sensory, and psychogenic. Each of these is discussed in detail, the last two being "spontaneous" and resting upon a cerebro-cortical mechanism, the probable nature of which is considered. Such spontaneous eye-movements are found in vertebrates lower than man, which also show the first three types, the basis for which must be sought in the sub-cortical brain centers.

Troland (178) has made measurements with fifteen spectral colors on the thresholds for the entoptically visible "blue arcs," which seem to represent a secondary retinal stimulation by the action currents of retinal fibres primarily excited. The threshold lies in the neighborhood of one photon intensity, but shows a distinct minimum in the middle of the spectrum, the spectral distribution of the threshold roughly resembling a reciprocal of the visibility function. In a second paper (179) the same writer gives the results of careful measurements of the apparent brightness of the blue arcs for various spectral stimuli over a wide range of intensities. It was found possible to determine this brightness with considerable accuracy by introducing an objective comparison field of variable intensity. The data, as tabulated, indicate that the magnitudes are substantially independent of both wave-length and intensity, being in the neighborhood of a thousandth of a photon. A special series, with a red stimulus, using intensities between limits of ratio: 32/1 shows very conclusively the tendency of this phenomenon to follow a principle of "all or none." From this result it is inferred that the retinal action currents also follow the same law, which has been shown to hold for the excitation of motor nerves. Some of the difficulties which ensue with the application of this principle to visual response, are discussed in a preliminary way.

Rössler (161) has made determinations, in fifty or more individuals and under various conditions, of the relation of the blind-spot to the horizontal meridian. In general, the center of the spot lies underneath the retinal horizontal, a fourth or fifth of its area normally projecting above this line, although variations between one-half and a tenth are found in individuals. Both eyes are the same in the same individual. Inclination of the head, which is only partially compensated for by the concomitant rolling of the eyes, and also the latter movement independently, change the relation of the experienced horizontal to that of the retina and hence alter the apparent positions of the blind-spots in the visual field. The literature on the blind-spot is reviewed.

Tedeschi (177) states that the formula of Weiss applies to the electrical excitation of the retina, but fails for its luminous excitation. The chronaxie of the optic nerve is only about one-tenth that of the retina.

VI Ocular Hygiene

Ferree and Rand (48) have made a detailed experimental analysis of the effect of the intensity of artificial illumination upon the practical efficiency of the eye. The conditions in the present work were such as to avoid all glaring surfaces in the field of view, as these have a harmful influence. The subjects included persons with small errors of refraction as well as with normal vision. The results uniformly favor the higher illuminations, since the latter bring increased visual acuity—especially with eyes having defective refraction—increased speed of discrimination, increased speed of adjustment for clear seeing at different distances, and increased ability to sustain such seeing with any given size of test object. If the size of the test object is reduced so that its relation to the threshold is the same as for lower illuminations, there is no appreciable increase in the ability to sustain clearness of seeing for the normal eye, but considerable increase for the astigmatic eye. There is no greater general ocular fatigue (as from reading) under the high than under the low illuminations. Intensities were employed ranging between 0.001 and 36.0 foot-candles. The data are tabulated and plotted. The same writers offer a new account (49) of their work, already published and reviewed (1919), on the effect upon visual efficiency of the light from gas mantles having varying proportions of thoria and ceria. They find that increase in the greenish tinge of the light is detrimental, so that low percentages of ceria (0.75 per cent.) should be employed and a lamp shade of a counteracting color should be used. In general, color decreases visual efficiency but the warm colors are less detrimental than the cold.

Schanz (162) presents evidence that the proportion of ultra-violet in sunlight, etc., as well as the injuriousness of its effect upon the eyes have been underestimated. He is convinced, from a multitude of observations, that the constant fluorescence of the lens produces pathological changes which appear with age, and that under certain conditions the retina also is affected. He supports his contentions regarding the ultra-violet content of sunlight by experiments showing the great increase in the rate of growth of plants which are protected from the short-wave rays by means of glass. He has also constructed a photo-electric ultra-violet spectrometer, with which he finds important amounts of ultra-violet in sunlight, open arc, and nitrogen lamp spectra, as well as in the quartz mercury arc. Curves obtained by means of this instrument are plotted. Various glasses intended to protect the eyes from the injurious rays are discussed. Keiner (108) finds that the effects produced by rays from the mercury arc vary with the lamp which is employed, the one used by him emitting almost no rays which were transmitted by the lens and very few passing the cornea. No changes in the lens or the retina were observed, but there was considerable external reaction, including dilation of the pupils, conjunctivitis, keratitis, depigmentation of the iris, and sometimes local necrosis of the latter.

Wilson (184) analyzes possible factors involved in the irritation of the eye by motion-pictures. The Committee of the British Illuminating Engineering Society on this subject attribute the observed bad effects to the unnatural upward angle at which the screen is viewed. The present writer emphasizes the action of the dark-adapted retina with a brightly illuminated central area, having dark surroundings; also the great contrasts and rapid changes of the pictures, as well as the absence of natural colors. The source of the discomfort is in the retina, but there is no evidence that defects of vision are produced.

VII Twilight Vision and Duplicity Theory

Hecht is following up his very interesting studies on the photo-receptive process in molluscs, by a study of dark adaptation in the human eye and of the chemistry of the visual purple. Extant data on the course of dark adaptation (73) are first reconverted from the mathematically deceptive "sensitivity" form into the original threshold values. On the assumption, derived by analogy from the results with molluscs, that the initial photochemical effect is proportional to the logarithm of the stimulus intensity, these values lead to a curve representing the time change in concentration of the substances controlling visual excitability. The curve is that of a bimolecular reaction, and hence the analysis tends to corroborate the writer's conception that adaptation depends upon the recombination of two decomposition products into which the initially sensitive substance is broken up by light. It is supposed that the sensory effect in any case is proportional to the ratio of freshly formed decomposition products, due to stimulation, to the quantity of these already present. The sensitive substance is probably the visual purple, adaptation to any steady state of illumination involving a characteristic equilibrium between this pigment and its decomposition products. Pursuing these ideas further (74) Hecht reports careful and ingenious measurements, by a colorimetric method, on the time law of bleaching of visual purple, extracted from the frog's retina, under the continuous action of light. He finds the law to be that of a unimolecular reaction, without a period of induction or an after-effect. The purple was dissolved in bile salts, in which medium the reaction is not reversible as in the eye. The experimental procedure was such as to permit accurate determination of the bleaching rates, and the results indicate that the visual purple is a definite chemical entity which is broken down by light into simpler bodies. In both investigations, the empirical values fit the theoretical curves very closely, permitting the computation of constants for the equations of these curves.

Dresbach, Sutton, and Burbage (28) report briefly measurements by a "flash method," on the course of dark adaptation in the human eye. They find that the sensitivity rapidly increases within a half minute after daylight is cut off, and that in two to three minutes it has doubled or trebled. It continues to mount for about an hour. Fluctuating regional differences between nasal and temporal portions of the field were noted. The general zone explored was 10-15 degrees from the center of vision, a variety of test field sizes between one and ten degrees being employed. Nakamura (132) has made an ophthalmoscopic study of changes in the appearance of the retina in cases of stationary hemeralopia, as a result of prolonged dark adaptation. In these cases the retina ordinarily looks abnormally white, with a very strong reflex, exhibiting the blood vessels very clearly by contrast. Dark adaptation for one and a half to two and a half hours, however, causes the retina to assume the normal, dark red color, with a much reduced reflex, and at the same time there is a marked increase in the sensitivity of the eye to light. The injection of adrenin brings about a temporary return of the abnormal state, even in darkness. Dark adaptation in these subjects does not begin at once, but commences suddenly after an hour or more following exclusion of light. Although the author does not interpret his observations, they would seem to be associated with the generation of visual purple.

Roelofs and Zeeman (160) point out that in tests of dark adaptation the center of the retina will be mainly responsible for the responses to intense stimuli and the periphery for those to weak stimuli. Disease of the central region will therefore principally affect high intensity vision and of the peripheral regions vision for low intensities. The literature shows instances of a confusion of local disorders of the visual field with essential disorders of the dark adaptation mechanism, attributable to this relationship. Albarenque (1) reports histological studies on the retina of *Azara Linn*, *Didelphis marsupialis*, a highly hemeralopic animal revealing an absence of cones. The inner portions of the rods are indistinct.

VIII Color Campimetry

Ferree and Rand (50, 51, 52) report a continuation of their systematic studies on the distribution of color sensitivity over the retina. One of the problems which they attack (50, 51) is that of the absolute limits of chromatic sensitivity for various spectral stimuli as well as the influence of intensity upon the apparent limits. They find that spectral red (670 mμ), yellow (581 mμ) and blue (468 mμ) can be sensed as chromatic to the extreme peripheral limits of achromatic sensibility but that the green (522 mμ) falls short of these latter limits, the extent of the field for green not being appreciably increased by augmentation of intensity. Parallel experiments with Hering papers lead to similar results. Absolute blindness to green exists in the subject examined for angles with the center of vision greater than about 69°, while other colors can be perceived as such up to 92°. Work was done with the light adapted eye in a light room, 16 meridians being explored, with a wide range of intensities, although the widest variety of intensities were employed only in the temporal and nasal meridians. As the writers have previously established, a large intensity change is required greatly to modify the limits of chromatic sensitivity in the extreme periphery. The results are tabulated and graphically presented in full and care is taken to specify the brightness values of the preëxposure and surrounding field in each case. In a further paper (52) the same investigators report detailed studies on the effects of the brightness of the preëxposure and surrounding field upon results obtained in chromatic perimetry. These two factors, which are often neglected in such work, are found to exert a very powerful influence on the results and may be responsible for the apparent unreliability of perimetric determinations in clinical practice, since some sort of preexposure and surrounding field cannot be avoided. The present work was done under an illumination of 42 vertical foot candles. It was found that the widest angular limits of chromatic response exist when the preëxposure and surrounding field have the same brightness as that of the test field. Contraction of the limits by amounts as great as 20° may result from a combined effect of deviations from these conditions for the two factors in question. On account of the abrupt falling off in the chromatic sensitivity in the periphery these effects denote a very large sensitivity change. The depression of sensitivity by dark preëxposures and surrounding fields is greatest in the more peripheral regions, while that of bright values for these two factors is greater in the more central zones.

Ebbecke (30) has made a careful study of the color blindness and weaksightedness of the margin of the blind-spot. He finds that in general this region of the visual field is similar, both in its chromatic and achromatic response, to the peripheral region, although the relative numbers of rods and cones around the papilla are the same as those in other parts of the same retinal circle. Several procedures are described for demonstrating the lowered visual efficiency of the region around the blind-spot. The writer argues that this reduction in visual efficiency rests upon the dropping out of links in the impulse conduction mechanism which are involved in the original superposition of color sensitivity upon brightness sensitivity, the chromatic mechanism naturally disappearing first in any general reduction of function.

Engleking and Eckstein (38) have made a careful experimental determination of the best pigment colors for use in the perimetry of the color sense, with a view to improving the at present very low accuracy of such measurements. They have chosen a standard red, green, yellow and blue which are invariable in hue, of equal saturations and of equal peripheral, scotopic luminosities. Pigmented papers and cut-outs satisfying their formulae are obtainable (39) from Speyer and Kärner, Universitätsbuchhandlung, Freiburg in Br. These include a gray of the same luminosity as the colors.

IX Color Blindness

Schiötz (163) reports new data on the relative frequency of color blindness in males and females, finding 0.91 per cent. out of 2200 girls to be deficient in color sense, 7 being deuteranopes, 13 deuteranomalous. Among 2005 males 10.7 per cent. had a defective color sense. These data are found to agree closely with those of earlier statisticians. The principles of the Mendelian heredity of color deficiency, on the assumption that the latter is a sex-linked recessive character, are then developed in detail and it is shown that, on the assumption of 10 per cent. color blind males the occurrence of this defect in females should be 1 per cent., which evidently fits the statistics very satisfactorily. In the second installment of this paper Schiötz analyzes pedigrees in various color blind families and discusses Göthlin's principle that the nature of color blindness in the same family remains constant. The total number of color blind women thus far found by the writer is 36.

Wirth (185) finds from the study of 34 cases that 53 per cent. of color blind individuals exhibit anomalies of face color, especially a hectic redness of the cheeks. A combination of these data with data on normal individuals yields a correlation coefficient of 0.66 between color blindness and abnormal facial color. Among explanations of this fact the most plausible seems to be that both anomalies are symptoms of a general constitutional weakness. Edridge-Green (34) offers in connection with his book on color vision, 24 cards for the testing of color blindness. Each of these has a large number of irregular colored patches or spots, the shapes of which are the same on all of the cards although the colors differ. Camouflaged among these is a letter which the examinee is required to name.

Hess (80) has made a series of new studies on red-green blindness and reaches the general conclusion that red-blindness (protanopia) represents a stage of degeneration of color vision similar to but of greater degree than green-blindness (deuteranopia). In support of this view he finds that color equations established by the red-blind, at relatively high intensities and light adaptation, hold for the dark adapted green-blind eye if stimuli are proportionately decreased in intensity. With a projected spectrum the visibility limits were at 650 mμ for the red-blind compared with 675 for the normal, the brightest part of the spectrum being at 550 for the red-blind and 580 - 585 mμ for the green-blind. There was a tendency for the maximum point of the dark adapted green-blind to coincide with that for the light adapted red-blind. With decreasing intensity the maximum shifts less for the red-blind than for the green-blind and at very low intensities both are the same in this respect as the normal. In detecting variations of the proportions of blue and yellow in a mixture the red-blind show much less sensitivity than the normal, whereas the green-blind show greater sensitivity. Certain pupillo-motor measurements indicate that the effect of saturations of blue and yellow are less for the red-blind than for the normal and green-blind. In another paper Hess (79) reports results of determination of the color fields and other indices of chromatic sensibility for individuals who make abnormal equations of a red-green mixture compared with a yellow (the Rayleigh equation). On the basis of his findings he objects to the current uniform interpretation of such abnormality as an indication of color-weakness. In order to describe the facts without theoretical prejudice, a new terminology is necessary, according to which individuals making a normal Rayleigh equation are said to exhibit "red-green equality," while others exhibit "red-green-inequality"; but such classification does not permit us to discriminate between the color-weak and the color-strong. These statements are based upon the following experimental findings. Green-sighted individuals, who require an excess of red in the Rayleigh equation, show normal limits for red in the visual field but limits wider than the normal for green. The red-sighted show limits for both colors varying on either side of the normal, although always with the green narrower than the red. The blue and yellow limits for both types are in general the same as for the normal. These indications of specific chromatic sensitivities gained from a study of the color fields are supported by their close correlation with chromatic thresholds in the fovea and by other color functions, such as those demonstrated by Guttmann as symptoms of color-weakness.

Guttmann himself (63) presents evidence that the localization of the mechanisms for simultaneous chromatic contrast in anomalous trichromatics is not central, and is probably retinal. It is a fact previously established that such contrast is more intense in these subjects than in the normal. The present experiments involved a comparison between monocularly and binocularly constituted contrast patterns, it being found that the former elicited the supernormal contrast effect while the latter failed so to do. With the binocular field the threshold for the addition of green to a gray was found to be nine times as high for the anomalous trichromatic as for the normal, while with the monocular field it is lower. In other words, the contrast effect is aroused in the anomalous subject only when the compared stimuli are presented on the same retina, greenness being experienced by the anomalous only as a result of retinal color contrast. Guttmann, further (64), has continued his studies on the after-image processes in various types of color vision, and confirms his previous observation that after-images last only about two thirds as long in anomalous trichromatics as in the normal subject. There is also more frequent failure of the after-images to appear than in the normal. The greatest difference is with an orange-yellow stimulus and the least with a red one; other spectral colors used being yellow-green and blue. The effect is proportional to the degree of the anomaly, and in conjunction with the writer's previous demonstration of the high fatigability of the color sense in the anomalous it indicates that at least a portion of the defect lies in the receptor mechanisms. Inconclusive tests indicate that dichromatic and ordinary anomalous subjects have similar after-image durations, the similarity of their qualitative phenomena having previously been demonstrated.

Hess (76, 78) has devoted considerable attention to the devising of improved means for testing the color sense, both clinically and scientifically. Since fixed pigment colors can never be relied upon in accurate work, he offers several types of apparatus which permit the continuous variation of the colors and brightnesses of the stimuli to be compared, so that the subject can establish actual equations. Color filters—some in wedge form—reflecting surfaces with variable angles of light incidence, and Nicol prisms are employed. The devices include one having a variable colored spot, for testing railway and marine personnel. Methods are described for applying the apparatus to the analysis of hereditary and acquired deficiencies, individual differences, and the determination of the limits of the color fields. Jennings (99) reviews clinical and office methods of testing color blindness, while Edridge-Green (36) describes a new spectrometer for the analysis of color blindness and normal color vision.

X Interaction of Visual Areas

Hess (81) presents evidence against the "unconscious judgment" explanation of simultaneous contrast. He shows that an original brightness pattern showing intensities of ratio 1 : 800 can be rendered invisible—through contrast depression of the sensitivity—by the action of a very bright surrounding field. The magnitude of the contrast effect, both for brightness and chroma, is proportional to the difference between the contrasting areas, it being incorrect to regard low illuminations as especially favorable. The contrast action is practically instantaneous. Measurements (76,

p. 45 ff.) of the amount of red which must be added to a test field in order to counteract the contrast effects of various proportions of red in a surrounding field show, in agreement with the results of Pretori and Sachs, a linear relation between the two. Hess also reports the discovery of new phasic processes in visual excitation which are produced by a combination of changes in the intensity of the stimulus with either an objectively or subjectively produced contrast between adjoining areas.

A number of investigators have studied the effect of contrast upon brightness discrimination. An elaborate series of measurements on two subjects lead Schjelderup (164) to conclude that Weber's law, in vision, is merely a special case of a more general principle expressed by the equation: $\Delta i = ai + bI$, where i is the intensity of the test field stimulus, I that of the surrounding field, and a and b are constants. When i is greater than I Weber's law holds approximately, but with the reverse condition it breaks down seriously, and with fields smaller than one degree under the latter condition, the threshold may become independent of the test field intensity, but proportional to that of the surrounding field. The effect cannot be explained in terms of adaptation, ordinary simultaneous contrast, or central inhibition, and hence must be regarded as a new form of interaction of visual areas. This interaction develops rather slowly, and the more slowly the larger the stimulus field. It can be explained by the assumption of a diffusion of fatigue products from the surrounding field into the test field, causing a depression of the activity in the latter. The data and quantitative reasoning are presented in full. Dittmers (27), studying this same problem independently, finds with eight subjects and a single field size (1° 12′) that the discrimination threshold shows a minimum with respect to the brightness of the surrounding field when the latter is equal to that of the test field. There is also a minimum of the relative threshold when the brightness of the test field is varied with the surrounding field constant, if certain limits are not exceeded. His results agree with those of Schjelderup (and Cobb), but not with those of Jaensch (97) whose experiments lead him to conclude that the discrimination threshold is independent of brightness contrast for a constant intensity of the test field. The basis of the discrepancy probably lies in the limited range of conditions tested by Jaensch.

The latter's interest is primarily in the relation between the laws governing brightness contrast and those controlling the "color constancy of visual objects." This tendency, manifested by visual perception, to represent the reflection characteristics of objects, regardless of the illumination, is described as "transformation." Katz has shown that transformation does not influence the discrimination threshold and argues that it also involves no change in intensity of the underlying physiological process. Jaensch endeavors to avoid this latter conclusion. In another, very elaborate paper, Jaensch and Müller (98) have demonstrated an extensive parallelism between the laws of transformation and contrast, although maintaining the distinctness of the two processes. Their experiments, as reported in detail, show that the degrees of the two effects are approximately proportional to the given brightness of the test object, as well as to the magnitude of the given brightness difference, any deviations—such as occur with small brightness differences—from these relations being exhibited equally by both effects. The influence of changes in the local or general intensities, upon the apparent brightness relations is the same in both phenomena, for example: equations established by the aid of contrast or transformation remain valid with proportional reduction of all of the intensities. The law of Hess and Pretori, in expanded form, holds for both effects. The two papers dealing with this subject belong to a series on fundamental questions of color psychology to which Jaensch writes a general introduction (96).

Clément (14) comments on the rose-colored halos which can be seen about a phosphorescent zinc sulphide (green) screen viewed in the dark. The time required for their generation is less than one fifth of a second and their area may be 150 times that of the screen.

XI Temporal Relations of Excitation

Bills (6), working in Ferree's laboratory, has made a very thorough study, apparently on only a single subject, of the curves of rise for the brightness attribute of the sensations evoked by four typical spectral stimuli, which were made photometrically equal at several intensity levels. Her monograph begins with an elaborate review and criticism of the work done by previous investigators, the methods employed by Broca and Sulzer, Exner, and Kunkel being re-applied by the present worker with some improvements. In addition, three new methods were utilized, the measurements in which were so calibrated as to permit reduction of the results to a j.n.d. sensation scale. The principal emphasis is laid on the time required for the sensation to reach its maximum, but complete curves of rise are plotted. The results vary somewhat with the method employed, but concordance is better with the new than with the old procedures. The times to reach the maximum range from 0.06 to 0.21 second, in nearly every case the yellow (580 mμ) showing the greatest speed, the blue (463 mμ) tending in general to be the slowest. The "cold" colors—blue, green (511 mμ), and white—seem to require more time than the "warm" colors —red (686 mμ) and yellow. These rules are not universal, however, as there is considerable variation with intensity as well as other factors. The intensities used varied from 0.057 to 1.21 meter-candle, on a white surface. The reviewer has been unable to determine from the data given, what angular size was possessed by the stimulus field, which leaves in doubt the relative degrees of participation of rod and cone process in the excitation.

Piéron has continued his careful measurements of the minimum energy (or light) required to produce vision with brief stimuli under various conditions. Measurements in the fovea (146) show in agreement with the work of Grijns and Noyon, a minimum of the energy threshold at about 0.02 second exposure. From 0.002 to 0.080 second the law of Bloch is approximately followed, while that of Blondel and Rey holds between 0.100 and 1.0 to 2.0 seconds. For extremely brief exposures the energy increases greatly. Tables and graphs show the energy required for exposures up to 3.2 seconds, both for light and dark adaptation. The curve is analogous in all respects to that established by Lapicque for the electrical excitation of nerve. In a second communication (148) the same author presents parallel data on peripheral vision, a small stimulus field 20 degrees from the fixation line being employed. Red and blue filters were used to isolate rod from cone response in two series of measurements. The cone curve, plotted in terms of the minimum threshold as a unit is practically the same as in the fovea, showing a minimum at 0.030 second and a limit of summation at 3 seconds. The rod curve is similar in form, but with quite different constants, the minimum occurring at 0.002-0.003 second, and the summation limit at 0.8 seconds. This implies that the excitation process is much more rapid for the rods than for the cones, and the threshold for the former is also naturally much lower than for the latter, the ratio varying from 1/315 at an exposure of 0.005 second to 1/90 at 0.800 seconds.

In further papers Piéron considers the influence of the size of the stimulus field upon the threshold. In peripheral vision (147), with conditions as specified above, the use of fields varying between 20″ and 33′ 20″ shows that within certain limits the areal summation for the cones is seven times that for the rods. The product of intensity and area tends to be constant for the cones but not for the rods, but for the latter the product of intensity and field diameter shows constancy above a certain size. Continuous, rather than momentary stimulation was employed in these experiments, and the results are explained in terms of the relative densities of packing of the receptors in the retina. Further experiments (146) show that the laws of areal summation in the fovea—for cones—are the same as those for the peripheral rods, and hence indicate that these laws—in contradistinction to those of temporal summation—depend upon the sizes and distributions of the receptors rather than upon their specific physiological characteristics. When exposure and area are varied simultaneously, it is found that both peripheral rods and foveal cones, the lowest values of intensity multiplied by time, involve very brief durations and relatively large fields. Quantitative data on this relation are tabulated.

Ebbecke (31) points out the importance of a study of momentary vision as compared with the protracted vision of many experimental procedures and the wandering gaze of ordinary life. His own extensive observations with very rapid opening and closing of the eyes, show that this procedure reveals many features of the first stages of optical excitation, such as the following: (1) great brightness and low color saturation, (2) prominence of irradiation and simultaneous contrast effects, (3) presence of entoptic figures. These various appearances are analyzed in detail, and explanations are suggested in terms of local adaptation and the like. At low illuminations the momentary sensation is darker than the normally prolonged one, but at high illuminations it is brighter. The non-appearance of these phenomena in ordinary vision must depend upon a normally operative process of retroactive inhibition, the physiological mechanism of which is considered. Ebbecke (32) has further made careful studies of vision under flickering or intermittent illumination, which shows features closely resembling those of momentary vision, as discussed above. It has the characteristics of the phase of excitation which immediately follows the period of rise, but relieved of the retroactive inhibition of ordinary continuous vision. In addition to the features already indicated above, there are complementary color phenomena, associated with the periodicity of the chromatic excitation. The author has discovered what he considers to be some new flicker effects, and presents explanations of chromatic induction by white stimuli on the basis of the usual adaptation of the retina to the red of the blood-stream.

Monchy (130) shows that the phenomenon, described by Wassenaar, of an initial bright phase, followed by rapid darkening, when the closed eyes are suddenly illuminated, is easily explained by the contraction of the pupil behind the lids. It does not occur when mydriatics are administered. Cobb (15a) points out that in ordinary life, visual stimuli are momentary as compared with conditions in many laboratory experiments, such as were carried out by him on the influence of extreme types of light distribution upon the discrimination threshold. The failure of such experiments to reveal ill effects of the distributions comparable with those resulting in everyday life, may be attributed to the undue elimination of factors involved in the constant readjustment of the ocular mechanism to changing stimuli. Forsythe (56) presents a detailed account of his tests on the best conditions for signalling by means of light flashes. Three observers agree that the best ratio for dot : dash : space is 1 : 4 : 3, in duration. Speeds corresponding to 9 to 13 five-letter words per minute can be attained, failure generally being due to inability to distinguish the dots. The technique of the work is described in detail and the results tabulated in full.

Hardy (65) has studied the persistence of vision for various colors for his own eye at more than 100 points on the retina within a circle of radius equal to 40 degrees, his results permitting him to plot loci of equal persistence which, for the red stimulus, are circles slightly flattened parallel to the horizontal meridian. For the red stimulus (677 mμ) the persistence decreased approximately in proportion to the distance from the fovea, the minima and maxima being 0.0209 and 0.109 seconds. Similar results were obtained for the yellow-green, which varied between 0.0179 and 0.0339 seconds. The blue-violet (463 mμ), however, showed very little variation: 0.0305 to 0.0401 seconds. The data are not presented in full.

Pütter (156) continues the detailed development of his general mathematical theory of excitation processes, based upon chemical assumptions, dealing in this seventh installment with the subsidence of the excitation, which includes adaptational "recovery" as well as "decay of sensation." The specific applications are almost exclusively to vision. The fundamental equation of excitation, derived from the general theory,—besides explaining satisfactorily the empirical low of "decay"—indicates that the degree of excitability of a single element system should be an exponential function of the time of recovery. Comparison with Aubert's data show that this relation holds for the fovea, but it fails to satisfy Piper's results for the periphery. The difficulty can be met, however, if we assume in the latter case a system of simultaneously recuperating elements. The mathematics of this assumption are worked out in detail. The appearance of both positive and negative after-images in the completely darkened eye can be accounted for if we involve in the system not only a sense-cell but a ganglion cell for which the excitation material of the sense-cell is the stimulus. Related developments of the idea of concatenated elements serve to explain measurements on threshold "light-gaps" in harmony with the general theory.

Hess (81, p. 65 ff.) confirms his previous observations that the Purkinje after-image is visible in the fovea, after protracted dark adaptation. It can also be obtained with red light, in which case it has a reddish hue. These facts refute the view that it is attributable to a retarded response of the rods.

Allen (2) presents a second description of his important studies on the differential effects of fatigue with spectral colors, upon the critical flicker frequencies for the same or other spectral colors. These experiments, as reviewed in our Summary for 1919, divide the spectrum into definite regions and strongly corroborate the three-sensation theory of color vision. Incidentally, in his present paper, Allen offers a valuable review of color vision hypotheses in the form of a geneological tree.

Sheppard (172) reports extensive experiments on the changes in the attributes of the sensations due to continuous chromatic stimulation in the fovea, which support the deduction from Hering's theory that equilibrium adaptation yields uniformly a neutral mid-gray. He used surface colors in direct sunlight as well as under lower illuminations, and also pure spectral color at various intensities. The times required to produce the gray varied from 40 to 220 seconds. The introspective accounts given by the subjects are reported in detail. In the case of the spectral stimuli the time required to yield a gray for different wave-lengths was found to correlate positively with the chromatic threshold, thus showing the saturation of the colors to be its principal determinant. Only in the case of the spectral stimuli was an artificial pupil employed, and occasionally difficulty was experienced in obtaining the neutral gray with high intensities under these conditions, a fact which the writer attributes to eye-movements, since very high intensities with filters gave the gray. The fovea has a longer time of adaptation to color than other parts of the retina. Juhász (106) has carried out experiments, having a similar bearing, on the conditions influencing the production of complementary colored after-images of a 2.6 degree color filter field in various surroundings, projected on gray reacting surfaces of various brightnesses. He finds the latent time of the after-images to be independent of the intensity and duration of the original stimulus but the duration and clearness of the after-image increased with the intensity. Preëxposure times ranging between 12 and 30 seconds were employed, and the durations of the images varied from 10 to 55 seconds. The shortest preëxposure time which would give a complementary after-image was found to be from 5 to 7 seconds and near this exposure the latent time is somewhat prolonged. The duration of the after-image increases asymptotically with that of the preëxposure. The image both appears and disappears more quickly on a bright than on a dark projection field. Periodic fluctuations of the images, accompanied by spontaneous darkenings were noted. Experiments were made with projection fields which were brightened or darkened by contrast, such subjective brightening being found to hasten the disappearance of the image but subjective darkening did not completely compensate in this respect for objective intensity. The latent time decreases and the clearness and duration of the image increase with increase in the size of the original stimulus field. The "white light" of the projection surface is regarded as accelerating the process underlying the after-image, its effect being similar to that accompanying the addition of a subjective white to the corresponding color sensation.

XII Theory of Chromatic and Achromatic Vision

Schjelderup (165) outlines a new theory of the mechanism underlying color vision, which he finds to be capable of accounting for all known types of color blindness. After carefully reviewing the numerous deficiencies of the Young-Helmholtz and Hering theories, with their various developments and modifications, he turns to the general conception of Von Kries' "zone theory," which recognizes the existence of successive stages in the visual response with distinct mechanisms, as a means of satisfying the complexities which are met. The writer believes that at least three such stages must be distinguished, the retinal, the cortical, and an intermediate stage. The cortical system consists of six independent processes, corresponding to the psychological primaries. Any one of these can drop out without disturbing the others. The intermediate system has six corresponding processes, related in antagonistic pairs in accordance with the Hering scheme, and these pairs must drop out together. In the retina, finally, there are three elements, which respond to stimuli of different wave-lengths in the same general manner as Hering's three substances, one being "oxidized" by all wave-lengths, while the other two are either "oxidized" or "reduced" according as the long or short waves are involved respectively. However, the correspondence of these retinal processes with the higher processes is not "one to one," but "one to many"; except in the case of the first mentioned process, which has an achromatic function only. The longest wave, chromatic receptor, for example, evokes not only higher processes for red, but also for yellow and white to a definite extent. This total system provides the materials for explaining a wide variety of phenomena, and its explanations of each of the recognized forms of color blindness are developed in detail. The frank acknowledgment in this theory of the necessity of complicated assumptions, as well as the author's sophistication and ingenuity, make it the most interesting of all recent efforts along this line.

Troland (180), in the first installment of a paper dealing with the difficulties encountered by explanations of color vision, emphasizes the need, which is met by Schjelderup's theory, of taking into consideration not only the retinal but the conductional and central factors in the process. Some of the facts concerning the part played by these latter factors, together with fundamental principles—such as that of "all or none" action in nerve—are discussed. The difficulties facing the standard theories are reviewed, and the Ladd-Franklin theory is recommended as the most satisfactory for pedagogical purposes, although lacking in realism. The general requirements of a scientifically adequate theory are considered, and some constructive suggestions are made concerning the representation of luminosity in the optic nerve impulse.

After reviewing the various classical theories of color vision French (57) propounds views of his own regarding the mechanism of form and color discrimination. The resolving power of the eye, as determined by contact patterns, coincides quite accurately with the dimensions of the foveal cones but can also be explained by the diameters of the diffraction circles. When the test of acuity is a coincidence of lines, as in a vernier, the precision is very much higher and, as recognized by Helmholtz, demands further explanation. The writer suggests a mechanism consisting of a division of the walls of the individual cones into three segments which are separately connected to the central nervous system by which, conceivably, the position of a stimulus point within a single cone can be perceived. This mechanism is supposed to be a part of the middle segment of the cone cell which segment constitutes the form apparatus of the receptor. Expectations regarding the appearance of small images derived from this hypothesis are found to be verified by experiment. The external segment of the cone is reserved to carry out the functions of color discrimination. This segment is divided into three portions lengthwise which are respectively sensitive to red, green, and blue light. Each of these portions is supposed to be connected to the brain by a separate nerve.

This so-called "series" theory of color vision is applied to the explanation of color blindness and chromatic threshold phenomena in which the reduction of general intensity causes the chromatic mechanism to go out of operation in the specified order. The explanation includes the Purkinje phenomenon. The difference between the rods and cones, according to this writer, is mainly quantitative, a stronger absorption of light taking place in the former than in the latter. Simultaneous contrast phenomena are explained by a mechanism involving the interconnections of the ganglion cells with the retina. The writer justifies the demand of his theory that each cone have six separate conducting elements attached to it by an appeal to the neurofibrillae.

Smith (172a), in a discussion, criticises French's theory on the basis, not only of the fineness of the nervous mechanism which it demands, but also because of the great power of intensity discrimination which is demanded by his three nerve mechanisms for the localization of a point within a single cone. An intensity discrimination of better than one part in 1090 is demanded for an accuracy of setting of one second. The remarkable accuracy obtainable in coincident settings can be explained on the assumption that eye movement, in conjunction with the quite irregular distribution of the cones in the retina, results in the successive stimulation of different selections of cones for accurate coincidence of abutted lines as compared with the case of inaccurate coincidence. Eye movements may also be brought into play to explain the fact of the perception of a white area as homogeneous on the asumption that there actually are three different kinds of cones respectively sensitive to three different colors. The eye movements bring about a confusion of the excitation in closely adjacent areas.

Constentin (19) offers a further development of his theory, previously advanced, which makes color discrimination depend upon the formation of standing waves in the retinal cones as a result of reflection, adequate reflection being absent in the rods, which merely record the progression of the waves in the form of achromatic sensation. Phenomena of color-matching between different stimuli are explained by the production of similar complex standing waves. The waves act on the nerve sensibility through the intermediation of electro-magnetic resonators, of which the neurofibrillae of the middle segments of the rods and cones form essential components. There are three differentially tuned resonators of this sort in the cones, but only one in the rods. Electrons and ions play a considerable part in the theory, which, however, is too vaguely conceived to be of much value. Dungern (29) also develops an hypothesis which utilizes the idea of standing waves in the receptors, as proposed by Rahlmann. He assumes that separate portions or strata of the cones contain resonators which are sensitive to different wave-lengths, the pairs: red-green, yellow-blue and green-violet existing together in the same three strata. Excitations occurring in the same stratum fuse, and there is some overlapping of responses, which explains the whiteness of all colors at high intensities. The red resonator responds somewhat to the waves which excite the violet. This scheme is applied to the explanation of facts of color mixture, color blindness, etc. As in Constentin's theory, the reasoning is difficult to follow.

Edridge-Green (33) has collected his views concerning the mechanism of color vision, and in particular his analysis of the types of color blindness, in the form of a book. Since practically all of the ideas which it contains have already been expounded by the author elsewhere, no attempt will be made here to review this work in detail. A redundancy of critical comments upon it have already appeared in many different journals. Notable among these are the criticisms by Sherrington (171) and Parsons (138). The former points to the absurdities resulting from Edridge-Green's view that the rods are not receptors, but manufacturers of visual purple, and to the conflict existing between his division of the spectral colors, his teachings concerning the influence of red and green fatigue upon spectral yellow, the presence of visual purple in the fovea, etc. and the findings of other investigators whose work he neglects to consider. Parsons (138), in a long paper, analyzes Edridge-Green's doctrines in great detail and brings forward overwhelming evidence in proof of their erroneous character in regard to the following points. All of the facts supporting the "duplicity theory" indicate that the rods are receptors. Edridge-Green's photochemical theory is not in harmony with physiological, physical, or chemical principles, and Houstown's mathematical development of this theory likewise encounters serious difficulties. The division of the spectrum into only six or seven colors is quite indefensible. The doctrine of the physiological unity of yellow is disproved by Burch's experiments, while the idea of the independence of color and luminosity vision is contradicted by the work of Abney. The views concerning the evolution of color vision are based upon very insecure data. Edridge-Green's explanations of after-images and contrast are essentially the same as McDougall's, to whom he gives no credit. His classification of types of color blindness is so complex as to be practically no assistance in their understanding. In open correspondence with Dunn, Parsons (139) exposits further his well-founded objections to the teachings of this provincial, yet popular, visual theorist. Edridge-Green's reply (35) is particularly weak, amounting to little more than a reiteration of his already published statements, and an appeal to his own prestige.

Three papers deal with the merits of the Young-Helmholtz theory. Berry (5) brings together various considerations which point towards the relative independence of luminosity and color vision. Black and white seem to be antagonistic processes similar to the complementary chromatic excitations, although with important differences from the latter on the side of the sense-organ. The cancellation of complementaries by one another should be said to *leave* white rather than to produce it. The luminosity of colors, as in the spectrum, is indicative of the intensity of the accompanying achromatic process. In color blindness and other pathological conditions, as well as under the influence of variations of stimulus intensity and position in the visual field, the light sense and the color sense can be impaired separately; indicating that brightness and color should be regarded as distinct forms of response to different aspects of a single stimulus. These considerations are deemed to conflict with the Young-Helmholtz theory, which regards luminosity as the sum of component color excitations. However, the writer does not reject the idea of a three-component chromatic system superposed upon a luminosity mechanism which is functionally independent of the latter. Peddie (142) maintains that the established fact of the trichromatic constitution of color vision necessitates the acceptance of the Young-Helmholtz theory which, in its general form, is not bound up with any particular conception as to the nature of the physiological processes which are involved. The theory is capable of accounting for all known or possible forms of color blindness. Even the Hering theory is actually a three-color hypothesis. Hartridge (66) also champions the ability of the Young-Helmholtz theory to explain the details of color blind cases, in particular the terms in which the green- and red-blind describe the spectrum. Their characterization of the red end as a "buttercup yellow" is thought by Dr. Pole to be inconsistent with the Young-Helmholtz explanation, but Hartridge shows by an analysis of Abney's curves that the reported color comparisons and judgments are exactly what would be expected from a dropping out of either the green or the red component excitations. The problem is largely one of the color terminology of the color blind observer, the long wave sensations being most strongly aroused by objects called yellow in both forms of the deficiency.

Among the most interesting contributions to the general theory of vision, during the year, are the papers of Hecht (71, 72), which are considered below under the caption of vision in animals. Lodge (119) suggests that the retina may contain atoms in a very unstable state, so that light will readily cause them to emit high-speed electrons, which will initiate the nerve impulse. He considers, further, the possibility of experiments to test this suggestion. Becke (4) as a result of extensive observations, is led to believe that the transformation of radiation into heat by the black pigment of the retina forms the essential step in the excitation of brightness sensation. He attributes color perception to the "mental reaction" to the absence of portions of the thermal excitation.

Pech (141) considers various physical and chemical processes which are oppositely influenced by the long and short waves of the spectrum, respectively. The cases considered by Pech are the bleaching of raw cotton, the production of erythrema of the skin, and the phosphorescence of zinc sulphide, all of which are excited by ultra-violet but inhibited by infra-red or long wave visible light. He concludes that when certain wave-length groups tend to cause a change in the equilibrium of a substance, in certain cases there is another such group which will counteract this change. The relevancy of these considerations to antagonistic color theories, such as those of Hering, Schjelderup, and others, is obvious.

Hirschberg (87) has prepared a detailed analysis, with extensive quotations, of the conceptions held by Greek thinkers concerning the mechanism of vision. His paper is a valuable contribution to the history of visual theories. Fröbes (57a) presents an analysis of advances made in psychological optics during three early historic periods: those of Greek philosophy, of Alexandrian culture, and the Middle Ages respectively. The doctrines of Aristotle and of Alhacen are given particular attention.

Coblentz (16) draws an interesting comparison between the response of the eye and of photo-electric cells, to radiation. The eye, regarded as a radiometer, resembles the photo-electric cell in the high degree of selectivity of its excitability by different wave-lengths. The visibility curve, for the eye, corresponds with the calibration curve of a photo-electric cell. Cells of the variable resistance type (selenium) show lags in the beginning and ending of excitation, similar in law to the corresponding visual effects, but the thermionic cells react almost instantaneously. The resemblance between such cells and the eye is in general not sufficiently great to permit inferences from the mechanism of the former to that of the latter; the wave-length selectivities are quite different as are the laws connecting the intensities of the responses with those of the stimulus.

XIII Central Factors in Vision

Pötzl (149) draws a fascinating parallel between the colored mists seen as a result of certain central disorders and actual hazes in physical space, which act by scattering light (Tyndall phenomenon). These subjective additions to visual space—reddish in the aura of epilepsy, yellowish in santonin poisoning, but seldom if ever bluish—behave for the subject as if they were real mists. An analysis of the phenomena provides evidence that in color vision, as in space perception, there is a coöperation of many different cortical elements, which may be separately affected in pathological states. The relations of these elements to mid-brain, optic nerve, and retinal mechanisms—as well as to the Young-Helmholtz theory—are considered. Gelb (61) gives a detailed account of disorders of color and perspective vision resulting from war injuries in the occipital region. In one of the cases studied there was complete color blindness and in the other, red-green blindness, together with loss of color-memory and imagery as well as amnesia for color names. There was reduction in the number of discriminable gray tones. The most striking characteristic of the cases, however, was the tendency of the remaining visual qualities to separate themselves from the surfaces of objects, losing their character as sharply localized "surface colors" and appearing indefinitely in the intervening space. The colors seem to the patient to have a thickness, which is greater the darker they are. The apparent transparency of the colors varies with conditions. Contrast and transformation (color constancy of visual objects) are seriously disturbed but still operative. A careful analysis, in fact, disproves Katz's principle that the existence of "surface-colors" is a necessary precondition of the phenomenon of color constancy, the actual requirement being the existence of "object-colors," *i.e.*, colors definitely associated with particular objects. There was gradual recovery from the above described pathological conditions, which seem to depend upon a form of "psychic blindness."

Coleman (18) has made interesting studies on the influence of the oxygen or carbon dioxide content of the blood upon retinal rivalry. The principal experiments were carried out with after-images, produced in various binocular patterns so as to form indices of the functioning of different halves of the same eye-field or of the total respective eye-fields. The condition of the blood was controlled by forced or inhibited breathing and by periods of muscular work. With a deficiency of oxygen the right and left fields alternate as wholes, and this alternation begins sooner—after stopping breathing—following muscular work, than otherwise. With excess of oxygen, the brightnesses and equality of images due to opposite eyes are increased, but the temporal and nasal halves of the single eye-fields exhibit interchanging alternation. There is no similar alternation between the upper and lower halves; and the writer infers that the low oxygen condition (with its accompanying "panoramic vision") utilizes the crossed fibres—of the optic nerve—only, while with adequate oxygen the direct fibres are also involved (yielding stereoscopic vision). Hoeve (89) continues his controversy with Igerscheimer regarding the form taken by scotomas due to injury to the optic nerve, and by an analysis of Igerscheimer's methods and findings sustains his view that such scotomas do not in general radiate from the blind-spot.

Fuchs (58) reports elaborate studies on disturbances of distance and direction localization, in three cases of hemianopia or hemiamblyopia. Objects perceived by the injured portion of the field suffer an illusory displacement in the direction of the uninjured portion. The investigation of this and allied effects by a variety of procedures indicates that the phenomena in question rest upon the same basis as the normal "concentric shrinkage of the visual field." The displacement is in the direction of the portion of the field which has the greatest clearness, and is thus most important to the attention, the apparent shrinkage of distances being proportional to the indistinctness of the perceived object. The displacement of the median plane in cases of hemianopia or hemiamblyopia can be explained in the same terms, the "center of attention" in the visual field shifting from the fovea in the direction of the uninjured half of the field. Applications of this general theory are made to phenomena of double vision, motion perception and disturbances of counting. Monbrun and Gautrand (129) describe three cases of double hemianopia in which macular vision was preserved, and one in which it was lost, the last case naturally being one of cerebrally conditioned, total blindness. A study of these cases proves clearly the independence of the cerebral mechanisms for central and peripheral vision, the conservation of macular vision in the face of extensive lesions being explained by the multiple representation of the macula in the cortex—in the most posterior portion of the calcarine fissure. Bollack (7) considers a new case of bitemporal hemianopia, resulting from war injuries in the region of the chiasma. He also reviews and classifies into two groups, the previously reported cases of homonymous hemianopia.

Jaensch (97a) reports preliminary methodological studies on *Anschauungsbilder* or memory after-images. These images are readily conjured up by many observers with great distinctness either soon after seeing the original object or after a considerable period of time has elapsed. The writer takes issue with the contention of Müller and others that these phenomena, as demonstrated in the work of Urbantschitsch, are inherently unamenable to scientific technique and are not governed by psychological laws. Experiments show that the law of identical visual direction and the phenomenon of retinal incongruence can be observed with these "intuition images." The existence of the latter phenomenon in connection with these images indicates that it does not depend essentially upon a retinal mechanism. Careful analysis shows that the images are not products of suggestion although the majority of observers were youthful. The images are often so distinct that they may be confused with or are capable of inhibiting actual sensations or perceptions. They are remarkably resistant to forces of suggestion and distraction, differing in this respect from images of imagination. The conditions most favorable to the scientific study of the phenomena are carefully analyzed, and a consideration of the work of Urbantschitsch indicates that with respect to these phenomena there are two classes of observers, those of stable and unstable dispositions respectively. A detailed analysis is given of the probable characteristics of these two dispositions.

XIV Visual Perception and Illusions

Carr and Hardy (13) have attempted a preliminary experimental analysis of some of the factors involved in the perception of relative motion. Generally speaking, the two elements in this perception are the judgment of relative motion and the judgment that one of the objects involved is stationary. The experiments were made with two lights seen against a completely dark background, one of these stimuli remaining physically stationary while the other was moved. It was found that accuracy of judgment as to which of the two stimuli actually suffered displacement was favored by (1) differences in size between the two stimuli or increase in their combined area (2) inequality of brightness and decrease of the combined illumination (3) fixation of the actually stationary stimulus. Amplitude of motion had no influence but the perception was more rapid with objectively increased speed. Consistent individual differences in ability were found. The results are tabulated in full. Dimmick (26) has carefully repeated and extended Wertheimer's experiments on the principles underlying stroboscopic phenomena, the primary problem being to determine the nature of the so-called *phi* phenomenon, which is described by Wertheimer as a pure motion sensation isolated from the stimuli proper. Wertheimer found five types of stroboscopic movement, and placed the optimal interval between the times of presentation of the two stimuli at 0.06 seconds. In the present work intervals between 0.03 and 0.15 seconds were employed, the durations of the two successive stimuli being 0.03 seconds, and eight subjects being utilized. All of Wertheimer's patterns were repeated, together with some new ones, and the optimal time was found to be 0.09 seconds. Each of Wertheimer's five types of movement was observed, but Korte's reverse movement could not be produced satisfactorily. The *phi* phenomenon, which is reported on the perceptual level as a pure motion intervening between two stationary objects, was found on the sensory level to consist in a "gray flash" occupying the space between the two stimuli. This flash had a peculiar perceptual quality and was visible not only on a dark but also on a bright background. It is regarded by the author as the actual substance of the motion illusion and its discovery dispenses with the utility of Wertheimer's neural short circuit theory.

Schumann (169a) makes a contribution to the introspective psychology of empty visual space. Different authorities have held divergent opinions concerning the inherent nature and the neurological basis of this form of perception. It seems necessary to admit the consciousness of three-dimensional visual space constitutes a form of sensation distinct from color whether the latter be chromatic or achromatic. The writer's experiments reveal the existence of what he calls a "glass" sensation which is capable of varying in a dimension designated as compactness. The sensation can be generated in very compact form by favorable stereoscopic settings, as well as in the ordinary perception of transparent objects. In its least compact form it constitutes our perception of ordinary visual space. The sensation fuses with colors in the general perception of solid objects, and is separated out for special attention only under relatively rare circumstances.

Zigler (188) reports experiments, suggested by Schumann's work on form qualities, relating to the visual perception of form and concludes that visual form qualities are identical with the meanings attaching to the sensations, the clews to which meanings are given by certain "attributive patterns." This work is on the borderline between psychology and applied logic. Lips (118) also considers in great detail another problem lying on the borderline between visual perception and psycho-physical methodology. He is interested in the situation in which two stimuli are compared with a third, and selects visual judgments upon the lengths of lines as presenting the clearest case. A tachistoscopic technique and parallel lines were employed. He finds that if two such lines, about 165 millimeters long, are different from each other by 1/80th of their length, false judgments concerning their relation to a third, successively presented, comparison line in general do not occur. Wheeler (183) reports in detail on the visual factors involved in the dreams of a subject 27 years old who has been blind since the age of 11. These dreams contain very definite visual imagery, with synaesthetic associations, which are of the same type as those operative in the waking consciousness of the same individual, a sort of disintegrated visual material forming the main substance of the subject's thought life.

Visual details are absent, but tactual data are almost inevitably translated into general visual forms which are filled in by tactual, auditory and kinesthetic minutiae. One interesting feature is the manner in which the individual visualizes himself at a distance, both in his dreams and his waking experience. Grünbaum (62) presents experiments in refutation of the view advocated by Jasper that the spaces of visual imagination and perception are not co-penetrative. Grünbaum believes that if it can be shown that the physiological expressions accompanying visual imagination are the same as those which go with perception, this constitutes evidence for the identity of the two spaces. His reported experiments provide evidence of this sort, the subjects being instructed to visualize a circle or a cross in certain definite positions in space, and successful visualization was almost inevitably preceded by movements of the eyes toward the given position. When the subject was instructed to inhibit such movements there was great difficulty in forming the required images, the time required being increased and nystagmus often resulting.

Dember and Uibe (21) report, among the results of their experimental studies at Teneriffe, data which lead them to advocate a "physical" explanation of the apparent flatness of the arch of the heavens as well as (22) the apparent increased size of the sun and moon at the horizon as compared with the zenith. In their first paper (21), after discussing various physical and psychophysical explanations of the apparent form of the sky surface, they advocate the view based upon Reimann's ideas that the contour in question is determined by the limiting distance through which vision can penetrate the atmosphere, as determined by the absorption and scattering of light. Formulae based upon this theory indicate a definite curvature for the dome of the sky and also a definite correlation of this with the photometric brightness of the sky at various angles with the horizontal. Photometric measurements combined with observations upon the visibility of small pilot balloons which were released for experimental purposes corroborate this view. There is some question as to whether this explanation should be called "physical" since the factor involved is obviously that of the secondary criterion of distance commonly called "atmosphere." In the second paper (22) the same authors explain the increase in the apparent size of the sun and moon near the horizon by noting that these heavenly bodies are seen projected upon the sky surface, their angular sizes being substantially constant, but since, as shown by their previous work, the zenith is visually nearer than the sky near the horizon visual sizes of the orbs will be correspondingly greater in the latter than in the former position. This explanation is verified by special experiments involving photometric measurements of the sky in accordance with their previous scheme, combined with psychological determinations of the apparent sizes of the sun or moon at various angles to the horizontal. An experimental test of Gauss's theory that physically equal angles of eye-movement have a lower value in upward than in forward gaze shows that the latter hypothesis is not adequate to explain the phenomena.

These astronomic illusions are attracting a great deal of attention from Teutonic thinkers. Lohmann (121) discusses critically the various explanations which have been offered of the apparently increased size of the moon and sun at the horizon and of the apparent form of the heavens, introducing numerous observations of his own. He concludes that the horizon phenomena do not depend upon physical characteristics of the atmosphere, but upon a collection of psychological factors, including enhanced interest, tendency to perceive the heavenly body as terrestrial, etc. The phenomena in question do not rest immediately upon the apparent form of the heavens, as claimed by some theorists. Various physical and psycho-physiological explanations of this apparent form are discussed, and the writer favors one based upon alterations in the mode of perspective vision, determined by variations of the angle between the line of sight and the ground, such alterations being psychological in nature but having physical and physiological determinants. Differences in apparent size between monocular and binocular vision of heavenly bodies at the horizon are noticeable.

Meyer (127) asks why the moon appears to be markedly reduced in size when viewed through a hole in a card although the hole does not interfere physically with the observation. Jaeckel (95) replies with a general theory of the basis of our estimates of the sizes of distant objects. According to his view, such estimates involve projection of the angular sizes of the objects upon a reference plane which is taken at a distance just indistinguishable from infinity by the accommodative mechanism of the eye. This distance, being a function of the diameters of diffusion circles upon the retina, is greater the larger the pupil, so that altered pupillary diameter—as in Meyer's observation, or in viewing heavenly bodies at the horizon as compared with the zenith—entails changes in the apparent sizes. The theory is worked out mathematically but appears to fit the facts rather poorly. The theory is attacked by Müller (131) on various grounds: use of erroneous acuity data, misinterpretation of Wundt's experiments on the part played by accommodation in depth vision, disagreement with perceptual facts, etc. The correlations between pupillary size and the apparent sizes of distant objects demanded by the theory are not found in actual observation. Horovitz (90) finds Meyer's phenomenon to be related with the alterations in apparent sizes which accompany the action of miotics, and which are attributed to a disturbance of the accommodation-convergence adjustment. Such alterations should also be expected to occur with changes in pupillary size, such as probably took place in Meyer's experiment. Although observations by the writer agree with inferences from Jaeckel's theory he does not consider the latter to be adequate.

Geipel (60) and Mohorovicic (128) also offer suggestions concerning the explanation of the apparent sizes of heavenly bodies, as incidentals to general theories of visual space. Both of these writers take their departure from Witte's comprehensive analysis of visual space, recently published (1918–1919). Geipel questions the generality of Witte's assumptions concerning the proportionality of apparent size to the retinal image, and finds that visual space follows the law of a rotation surface generated by turning one of the arms of an equilateral hyperbola around the line of sight as an axis. Witte's equations hold only as special cases. The theory is developed mathematically in considerable detail. Mohorovicic also objects to Witte's assumptions regarding the representation of straight lines in visual space etc., and develops mathematically a treatment of the subject to which Witte's doctrines are regarded as only a first approximation. Witte (186) defends his theories against objections raised by Seemann. These discussions appear to be opening up a new and interesting domain.

Köllner (114) has performed experiments to determine whether direction localization in monocular peripheral vision is referred to a Cylcopean eye, as is the case (Hering's theory) with foveal vision. His findings are in the negative, indicating that in the temporal half of the field the localization corresponds approximately with the actual position of the object relative to the given eye, while in the nasal half it follows a direction determined by projection upon the temporal half of the other retina, with binocular fixation of the object. This law holds for all distances of the object, and means that outside of the center of vision, direction localization is as if in the left side of the visual field the visual directions coincided with the *Blicklinien* of the left eye, while in the right side of the field they coincided with those of the right eye. Lohmann (122) discusses the problem as to why, in the case of vertically separated double images produced by prisms or oculomotor troubles, the image falling below the fovea in a given eye appears more distant than the other. He reviews the literature on this subject critically, introducing observations of his own, and in general agrees with Forster's explanation based upon the principle that in normal vision along a horizontal reference plane, objects at a distance greater than that of the point fixated form images below the fovea. Pech (140) believes that the normal retinal distortion of images is a factor in the perception of relief. This distortion—consisting of curvature of the image—increases from center to periphery, so that as an object approaches the eye there is a progressive increase in the deformation suffered by its retinal representation. By experience this degree of deformation becomes an index of the third dimension.

Wittmann (187) offers an historical and critical survey of the problem of the "invertibility" of real objects, the illusory perception of convex contours as concave or *vice versa*. He finds that real objects are thus invertible in binocular as well as monocular vision, although more readily in the latter. He describes new observations on the cube or *Dreikant* model and analyzes the case in detail. Observations are also reported on changes in apparent color and brightness accompanying the inversion process, as well as on the perceptual quality of "isolated objectivity" which attaches to the illusorily perceived object.

Howard (91) describes a new, compact precision instrument for measuring the binocular, depth perception threshold. The device, as constructed by a well-known firm manufacturing ophthalmic instruments, utilizes four wires adjustable in position by micrometer screws, in an arrangement adapted to produce a variable stereoscopic illusion. Edridge-Green (37) describes certain pictures which have a particularly stereoscopic appearance.

Jones (102) has developed in full the theory of his visibility meter previously described more briefly in other articles. This is an instrument originally designed to measure the effectiveness of various schemes for camouflaging ships by painting. After clearly defining the various concepts involved, the author analyzes the contrast factors concerned in the visibility of an object into those determined by brightness, hue and saturation respectively. The only one of these which can be handled theoretically at present is that due to brightness. The mathematical theory of this factor is developed in great detail and it is shown that the visibility of the object can be expressed in terms of the brightness of the background and the amount of generally supervenient light or "veiling glare" which will suffice to just render the object invisible. The visibility meter is so designed as to permit the supposition of any required amount of veiling glare upon the observer's view of the given scene as well as to provide a measure of the background brightness. Since this device reduces the visibility due to chromatic as well as brightness contrasts it can be employed as a general method for specifying visibility. A few concrete data are presented to illustrate the use of the instrument and the classification of factors involved into such terms as reflection factor, weather factor, etc., contribute to the practical significance of the discussion.

XV Response to Light in Lower Animals

Hecht (71), continuing his studies on *Mya arenaria*, adduces convincing evidence that the initial process in the response of this mollusc to light is photochemical in nature. Experiments with a considerable range of intensities show that the total exposure required just to set off the reaction is constant at about 5.6 candle-meter-seconds, so that the response follows the Bunsen-Roscoe law. It is also found that the temperature coefficient of the initial process is very low—1.06 for 10°C.—another characteristic of a photochemical action. These results further bear out the writer's hypothetical division of the receptor process in *Mya* into two phases. They also show that the classification of animals into those reacting to constant and to changing light intensities, respectively, is without fundamental significance; since *Mya* belongs in the latter apparent class and yet requires a definite and constant amount of light to produce a response. In a further study (72) Hecht finds that the relation between the measure of the initial process and the light intensity is logarithmic. The reaction times of the animals to a series of intensities—of equal duration—were first determined. From these the durations of the "latent periods" were computed, the latter being an inverse measure of the velocity of the chemical change which constitutes the second phase of the process. This velocity, in turn, is directly proportional to the concentration of products of the initial process. These relations, when fitted together, yield the logarithmic law above mentioned. The analogies between this law and those of absorption of light, of the photographic plate, and the psychophysical intensity relation are discussed. Incidentally, it is found that the Bunsen-Roscoe law holds not only for the threshold but for intensities up to ten times as great.

Hess is continuing his comprehensive studies of photic response in invertebrates. He has discovered (83) a new reaction in caterpillars—consisting of a bending of the anterior portion of the body—following a sudden decrease in light intensity. A study of this with chromatic stimuli demonstrates that these animals, like all other invertebrates thus far examined, have the same response to light as the totally color blind human eye. However, the caterpillars are also astonishingly sensitive to ultra-violet, even to wave-lengths less than 313 mμ. This is explained by the fluorescence of the substance in the external portion of the facet eyes, and the response of the animals to the ultraviolet may vary from that to their immediately visible spectrum because the fluorescent light is always non-directive within the eye. The structure and theory of operation of the facet eyes are considered in detail. The absorption of ultra-violet and the reactions of the animals to these rays are protective in function. Extant theories of animal tropisms are shown by these experiments to be based upon erroneous assumptions. Many arthropods (85) also show strong reactions to ultra-violet. *Polyphemus*, for example, in the light adapted state, reacts positively to radiation of low ultra-violet content, but this changes to a negative reaction with radiation rich in ultra-violet, especially in the dark adapted condition. Ants (*formica rufa*) are also extremely sensitive to ultra-violet, taking care not to place their puppae in these rays, although in their absence they seek the portion of the spectrum which seems to them the brightest. Bees seek the ultra-violet, *Chironomus* larvae react to its introduction or withdrawal, and daphnia always avoid it. The writer insists that, in spite of these selective reactions, arthropods have no true color sense. The comparison with the totally color blind human eye is, however, not completely satisfactory, since these animals seem able to distinguish the short wave radiations (blue and ultra-violet), regardless of their intensity. Fluorescence (82) lies at the basis of these differentiations in ants and daphnia, as in the case of the caterpillars.

Hess (84) further discusses the characteristic light reactions of certain invertebrates which did not prove sufficiently reliable for his quantitative investigations. The species considered include *Myrmeleo formicarius*, *Corethra plumicornus*, *Forficula auricularia*, *Bacillus rossii*, and *Lineus ruber*, as well as "*Doflein*," *Aphidinae*, *Hydrometra*, *Velia* (water spiders) and *Chironomus*. All of these show total color blindness. Many of them seek the blue in preference to the red end of the spectrum, but this is due merely to the superior brightness for them of the former rays. Minkiewicz's theories are completely refuted. Taliaferro (176) reports an extensive study of the reactions to light of *Planaria maculata*, with an endeavor to correlate them with histological details in the structure of the eyes. The animal has a definite negative phototropism, and sometimes shows orientation movements without preliminary trial and error reactions. Two reflexes, of twisting and wandering, respectively, are described, together with the manner in which these depend upon light intensity. Removal of both eyes destroys the orienting response, but not the movement away from the light, and also fails to influence the rate of locomotion. Removal of a single eye does not result in circus movements, and affects the reactions on one side only. The posterior and anterior portions of either eye have different reflex connections, as verified by selective excision of the portions in question, the animal turning in opposite directions when one or the other is illuminated separately. Removal of the posterior region does not affect the reactions of the anterior, but the converse is not true on account of the incidental severing of connections with the brain. The rhabdomes, or receptor cells—which exhibit a structure analogous to that of the rods and cones of the human eye—are stimulated only by light coinciding in direction with their axes. This fact, in combination with the shading action of the pigment cup in which they are held, is responsible for the control of the response as regards orientation. When the animal is once oriented in a horizontal beam of light, it receives no further orienting stimulus. In general, orientation is not necessarily dependent upon a symmetrical arrangement of photoreceptors.

Detwiler and Laurens (23) find that in general structure the retina of *Phrynosoma cornutum* is similar to that of the chameleon. There are no rods, although the cones are cylindrical in shape in the fovea, which lies within the maximally developed *area centralis*. At the edges of the fovea the external nuclear layer is ten strata deep, and the foveal cones are too fine to be measured with a magnification of three thousand diameters. The cones contain oil droplets, and there are no double cones. A large conical pecten is a prominent feature of the retina. Under conditions of ordinary illumination the pigment granules reach nearly to the paraboloids, except in the fovea, where the external segments alone are enveloped. Henning (75) has carried out experiments with birds and turtles which confirm Hess' statement that the spectrum is shortened at the violet end for the day birds, and indicate that both of these animal types possess a power of distance vision in mist or fog much superior to that of man. These two observations can be explained as a consequence of the absorption of short wave light by the red, orange or yellow oil droplets of the cones in such animals. Seeing at a distance through light-scattering media is much more efficient with long wave than with short wave light. This theory is supported by the differences in number and color of the droplets existing between day and night birds; as well as by considerations regarding the evolution of amphibia and reptiles. In such animals the entire retina functions like the yellow spot of the human eye.

Rochon-Duvigneaud (159), continuing his studies on the retinae of birds, develops further the problem of the interrelations of the two eyes and the functions of the foveae. Since birds have no direct (uncrossed) optic fibres, possess no power of eye-movement, and show strictly unilateral pupillary responses, it is highly improbable that they experience stereoscopic vision. Birds can be divided into three classes, according to the arrangement of their foveae: (1) Those having a single, approximately central fovea in either eye, the two optical axes making an angle of about 120 degrees (2) those having a posterior as well as a central fovea, with optical axes in general at less than 120 degrees, and (3) those with a single, posterior or lateral, fovea and optical axes at an angle of approximately 90 degrees. Even the latter have no direct fibres, although mammals—such as the cat—having about the same interocular angle, show such fibres. At present we have insufficient data to permit a determination of the lines of sight of the posterior or lateral foveae; but in general it seems improbable that any of the birds are physiologically Cyclopean, like man. Instead of furnishing reference points for coincident binocular vision, all of their foveae probably function separately and determine optical points of the compass in a comprehensive panoramic perception. However, we must know more concerning the central connections of the eyes and the lines of sight before these questions can be settled. It is difficult to understand why direct optic fibres are absent in many birds. Delage (20), reasoning from Rochon-Duvigneaud's findings that the lateral foveae of the *Rapaces diurnes* have the same functions as the central ones, bases an explanation of the existence of the former upon the manner in which these birds attack their prey. Observation shows that they drop upon their prey from above, their problem being similar to that of an aviator releasing a bomb. A mathematical analysis of this situation substantiates the explanation; the supernumerary foveae furnish acute visual areas directed, not transversely like the principal foveae, but more in the direction of regard as the animal falls upon its catch.

Schnurmann (166) has studied—as indices of visual sensitivity—the changes in skin color of *Phoxinus laevis*. Experiments on these reactions with chromatic and achromatic stimuli harmonize with the view that the photic response of this fish is the same as that of a totally color blind human looking through a yellow glass. The shortening of the spectrum at the violet end is explained by the presence of a protective yellow pigment in the eye substance. The mechanism of the response is considered quite fully.

Weve (182) has determined the relative sensitivity of seedlings of *Lepidum sativa* to representative chromatic stimuli. Brightly illuminated colored papers were placed on one side of the plant, and grays were found which when placed on the opposite side exactly counteracted the phototropic reaction to the color. The results show a spectral sensitivity curve with a maximum in the blue, closely resembling that of the photographic plate. The characteristics of this curve are contrasted with that which holds for the majority of the lower animals, with its maximum in the yellow-green, and conforming closely with that of the color blind human. The fact that plant response to light follows the Bunsen-Roscoe law, as well as the resemblance of its spectral excitability to that of the photographic plate, confirms the view that the fundamental effect is photochemical in nature. This applies also to animal vision, although in the latter case there is a radically different spectral sensitivity. Laurens (117) and Hooker have determined the sensibility of Volvox to wave-lengths of equal energy content.

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Abstracts and Reviews

The Relation of the Sighting Eye to the Measurement of Heterophoria

Percival Dolman, M. D.

WHEN the eyes are alternately covered and uncovered in the screen test, one eye is frequently seen to make a greater excursion of redress than the other. The subject during the parallax test occasionally notices that the image jumps further when the screen is moved in one direction than in the reverse. The question arises as to which of these two unequal eye-movements indicates the true deviation of the visual axes.

Evidently, under the screen test procedure, the rôle of fixation is given to each eye in turn. For the stimulus received by the retina of the eye fixing the test object determines the deviation of both visual axes when the other eye is screened.

But the screen test is not readily adjusted to make the measurements desired in this investigation. By means of the Maddox rod screen test the desired measurements could be made in a simple and accurate manner. "Either eye in this test may be selected for light-fixation, the other being covered by the Maddox rod. The fixing eye throughout the test is kept in the natural primary position, uninfluenced by any prism, screen or other device. The Maddox rod before the other eye is covered by a screen which is removed for an instant and replaced, allowing a brief view of the line of light. If the line does not pass through the spot of light, a rotary prism is placed in front of the Maddox rod and rotated while other brief exposures of the line are made until finally a degree of prism is obtained that causes the line to pass through the light every time the screen is removed. This prism is the measure of the deviation of one eye in relation to the other which fixes the light. It is obvious that a second measurement can be obtained by selecting the opposite eye for the rôle of light-fixation."

The sighting or dominant eye could in each case be determined by the observer by having him locate a distant light through a hole in a large card held in both hands. One hundred observers were taken at the Medical Research Laboratory, Mineola, Long Island, and of these tests for the sighting eye it was found that 61 per cent. used the right eye, 30 per cent. the left eye and 9 per cent. evidenced no preference. Of all these 81 per cent. gave two different measurements of the same type of heterophoria as a result of fixation of the light by each eye in turn.

"Out of 61 right-eyed observers, 47 exhibit the greater amount of some form of heterophoria when the right eye fixes the light. Of the 26 left-eyed observers, 19 exhibit the greater amount of error when the left eye fixes the light. The eye is used to fix the light during the test, the greater amount of heterophoria is exhibited by 66 per cent. of the observers, the lesser amount by 7 per cent. and the same amount by 17 per cent.

"Further analysis of the data does not help determine whether the greater or lesser amount of error represents the true condition of the eyes. If the purpose of the heterophoria test is to measure the maximum error, then the greater amount revealed by giving the sighting eye the rôle of fixation indicates a practical method of performing the test. This will give the greater amount of error in 66 per cent. of the tests and be accurate in 17 per cent. more where the same amount of error is recorded for each eye. It is possible then in 83 per cent. of the tests for heterophoria made by the Maddox rod screen method to measure the maximum error by having the sighting eye fix the light."

(Abstracted from *American Journal of Ophthalmology*, Vol. 3, p.258, 1920.)

On the Visual Requirements of Persons Licensed to Drive Mechanically Propelled Vehicles on Public Roads

Report of the Council of British Ophthalmologists

THIS rather lengthy report by the Council of British Ophthalmologists contains much that is of value to those interested in physiologic optics. We shall limit ourselves in these pages to the quotations of the considerations of this Council as contained under the heading:

The Various Kinds of Visual Defects in Motor Drivers from which Accidents May Arise

(1) *Blindness in, or loss of, one eye.* Persons who are blind in, or who have lost one eye, have a limitation of their field of vision, and can no longer see objects stereoscopically.

To compensate for the disadvantages occasioned by their limitation of field, those who have lost the sight of one eye generally learn to carry the head a little turned towards the blind side, so that the limitation becomes more equally apportioned on the two sides. They also in course of time instinctively acquire a habit of quickly moving the head towards the affected side, which enables them to mitigate to a considerable extent their disability.

Though, in motor-driving, stereoscopic vision is of some assistance in the judgment of distances, it is not the most important factor concerned; several others, such as parallax and aerial perspective, being of greater importance. Individuals who have never had the use of the two eyes are often good judges of distance.

The evidence which the Council had collected from drivers of mechanically propelled vehicles who become blind in, or have lost one eye, is in accordance with the above observations. They all considered themselves fully competent to drive, well able to take care of themselves when so employed, and capable of avoiding risks which would be likely to endanger the safety of others. Those who after cross-examination admitted having met with accidents, denied emphatically that such accidents resulted from their visual defect. Those who had lost the sight of the right eye, when questioned as to the difficulty of seeing on-coming traffic on the off-side, or traffic approaching from a cross-road on that side, did not admit having experienced any inconvenience. All had had a blind side for some considerable time and doubtless had acquired compensatory movements of the head. There is no doubt, however, that a person who had only recently lost the sight of an eye, particularly the right, would for a time experience considerable difficulty in such circumstances.

All the drivers dependent on the sight of one eye only, who were interviewed, admitted that they might find themselves disabled in the event of a foreign body getting into that eye, a disability which could only be guarded against by the habitual use of goggles, though the risk of it might to some extent be lessened by the use of a wind screen.

(2) *Conditions Necessitating the Habitual Use of Spectacles.* The habitual use of spectacles by a driver of a mechanically propelled vehicle might prove a hindrance to him in one of the three following ways:

(a) By restriction of the field of vision.
(b) By reduction of the acuity of vision in dim lights.
(c) By the glasses becoming obscured either from the condensation of moisture (outside from mist, or inside from the eye), or from being bespattered with rain or dust.

(a) The amount of the restriction of the field of vision occasioned by ordinary spectacles would be very slight, much less than that produced by the use of goggles. Such evidence as the Committee has collected from motor drivers does not seem to show that the restriction of field caused by the use of ordinary spectacles has proved a source of danger.

(b) In transmission through glass, loss of light occurs from absorption and also by reflection from the surfaces. In certain conditions of adaptation of the eyes to dim illumination, physical causes of this nature may more than counteract the beneficial effects of the correction of errors of refraction by spectacles.

(c) In motor driving obscuration of glasses by moisture from eyes only occurs in the absence of freely circulating air between the eyes and the glasses. It is not likely to occur, therefore, with the use of ordinary spectacles, or of properly constructed goggles where ventilation holes are provided in the surrounding material.

Obscuration of spectacles from without by mist, rain, or dust, can to some extent be guarded against by adaptable screens, extending from an over-hanging canopy above and from the footboard below, but not meeting. Such screens are provided in taxicabs and in most large motor cars. The drivers of motor omnibuses and tramcars have even less protection.

(3) *Defective Acuity of Vision Both With or Without Spectacles.* It is difficult to determine from the evidence at present available what degree of acuity of vision an individual needs if he is to drive a mechanically propelled vehicle with safety.

Further valuable information as to the influence which defective vision has in the causation of motor accidents might be obtained if the authorities were to institute an investigation into the visual capacity of drivers in a series of cases in which accidents have occurred.

In the Report of the Committee on the granting to partially disabled men of licenses to drive public vehicles already quoted, it was laid down: "That every man licensed should have two eyes and "that one of them, at least should be a good and normal one. If "the other eye were to some extent defective, but the vision were "fair, and the field of vision good, we do not feel that this defect "need be a bar, but we would not recommend any concession "beyond that."

The interpretation which the licensing authorities for hackney carriages in London put upon the terms "normal eye" and "fair vision" in the above Report, is as follows:

A "normal eye" is an eye with visual acuity = 6/6 as tested with Snellen's test types well illuminated, and with a full field of vision as tested by hand movement.

The term, "fair vision" is visual acuity = 6/24 as tested with Snellen's test types well illuminated and a full field of vision as tested by hand movement.

The evidence on which the "Maimed Drivers' Committee" based this part of its report was the expression of opinions by the witnesses examined and was not founded on definite instances of accidents occasioned by defective vision.

The standard of central acuity of vision required for chauffeurs by the army is, without glasses, in one eye 6/18 and in the other 6/60, no distinction being made as to which eye should have the better vision (A.C.I. 664, 1918). Many motor drivers employed by the army during the war had to drive heavy motor lorries along bad roads at night.

The Council have had a return of all the motor accidents occurring in the 1st and 2nd Transport Companies at Grove Park during the months of January and February 1919; 36 in all. The vision of the drivers in these accidents was obtainable in 14 cases, and it was found that central acuity of vision in the better eye in more than half the cases equalled 6/6, and in none of the cases was it less than 6/12. This evidence, for permission to use which the Council are indebted to General Sir J. H. Goodwin, K.C.B., D.G.A.M.S., shows that the accidents which occurred, in the cases investigated, could not be attributed to defect of vision.

The Council do not think, however, that the standard of central acuity of vision for motor drivers in the army under war conditions, when there was a shortage of labour, can be taken as a suitable standard for motor drivers of public vehicles in civil life, in time of peace, when there is an ample supply.

(4) *Restricted Fields of Vision and Night Blindness.* For the quick perception of on-coming traffic, or of objects approaching from either side, a full field of vision is the most important factor, rather than acute form sense in the centre of the field such as is tested by reading letters of different sizes in Snellen's test types.

It is from the stimulation of the peripheral portions of the retina that the approach of on-coming objects from behind, or from side turnings, is first perceived. It is, therefore, often the part of the retina which affords the earliest intimation of the approach of dangers which might culminate in collisions.

The presence of lowered acuity of vision in dim light, or of slow adaptation of the eyes from one light to another ("night blindness") might prove very dangerous to drivers of mechanically propelled vehicles which do not carry powerful headlights. They are conditions, therefore, likely to cause accidents in towns where the use of powerful headlights for motor vehicles is not permitted. The presence of a slight degree of night blindness is often difficult to detect without a very searching examination. For the purposes of motor driving the most practical test of a person's light-sense would be a trial trip at night, during which he should be required to show his capacity for steering a motor car in dim lights, and under varying conditions of illumination. This latter test would afford some criterion as to the time required for the eyes to adapt themselves from light of one degree of intensity to that of another.

(5) *The Presence of Diplopia or Squint.* A disordered movement of the eyes which causes a driver to see double must obviously be a serious source of danger in the steering of a mechanically propelled vehicle.

Disordered movements of the eyes may exist without double vision, the individual so affected using only one eye, suppressing the image formed by the other. Such individuals do not possess stereoscopic vision and are thus handicapped to some extent in their judgment of distances.

Disordered movements of the eyes causing one eye to turn inwards, "convergent squint," produce, besides the loss of stereoscopic vision, some limitation of the field of vision, on the side of the squinting eye.

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Practical Considerations in Connection with Insufficiency of Convergency of the Visual Axes

J. M. Banister, M. D., F. A. C. S.

THE author uses the term "insufficiency of convergence" to mean insufficient action of the adductor muscles of the eyes in securing and maintaining with ease the necessary degree of convergence of the visual axes in the coördinated muscular action required to secure single vision for points within infinity.

The adductor muscles, the ciliary muscles and the sphincter pupillae are supplied with innervation through the third nerve, the ciliary muscle and sphincter pupillae being supplied by this nerve through the ophthalmic ganglion.

"The nucleus of origin of the third nerve is situated in the floor of the fourth ventricle beneath the aqueduct of Sylvius. This nucleus, there being one on each side of the median line for its corresponding nerve, is a collection of ganglionic cells, from which the bundles of fibers, constituting the third nerve, proceed to the ocular muscles. Fibers ascend, also, from this nucleus to the angular gyrus of the cerebral cortex, which is supposed to contain the centers for the voluntary associated movements of the eyeballs (Bernheimer, Fuchs). Through a higher center, not yet located, but which is thought to be in the angular gyrus, it is generally assumed that the convergence of the two eyes is so coördinated as to secure single vision for points within infinity.

"Convergence is also associated with accommodation, both functions being, as before noted, under the direct control of ganglion cells in the nucleus of origin of the third nerves, and coördinated by the action of a higher center, or centers.

"This relation of convergence and accommodation was forcibly dwelt upon by Donders many, many years ago in advancing his views concerning the cause of internal strabismus, and is familiar to every oculist. Any condition which may have the effect of altering this relation between convergence and accommodation, as uncorrected errors of refraction, for instance, may be sufficient to induce convergence insufficiency.

"Landolt estimates that there must be in reserve for work at any given finite point, twice as much power of convergence as that required for securing single vision at that point, a fact which must be borne in mind in estimating the amount of convergence necessary for our patients."

Causes of Insufficiency of Convergence

The following is a list of causes as given by various observers:

1 It may be caused by a lesion of the brain or spinal cord (Landolt).

2 It may be a result of the neuroses. Neurasthenia may be particularly responsible. (Landolt.)

3 Anemia, or some debilitating disease, may be the cause (Landolt).

4 A real weakness of the internal recti muscles of congenital origin may be responsible (de Schweinitz, Landolt).

5 Errors of refraction and disturbance of accommodative efforts may induce the condition (Landolt, de Schweinitz, and many other observers).

6 Faulty attachment of the muscles (de Schweinitz).

7 Excessive action or spasm of opposing and dominating muscles (de Schweinitz).

8 Disturbances of innervation (Gould, de Schweinitz, Tscherning, Hansen Grut).

The most important factors are now considered by most observers as being connected with the innervation of the muscles connected with the function of convergence.

Symptoms

The chief symptoms pointed out include:—Marked ocular and mental fatigue after a short use of the eyes in near work are always the first symptoms. The print may dim, overlap or become mixed. Details, such as marks on the dial of a watch, may seem to broaden and then regain normal width, the process being repeated, showing a tendency to diplopia. As this condition becomes more established, increasing efforts of convergence will be necessary to prevent double vision and use of the eyes for near work will cause an intense nervousness in the spine between the shoulder blades. In walking, the ground may seem to oscillate and giddiness result and a similar oscillation may be noted in looking at objects around the room when indoors. Nausea and dizziness may result from close work. In locomotion the patient may feel as though falling forward or to either side. Tender regions make their appearance along the spine in the cervical and dorsal regions and burning spots or areas, on the arms or along the spine. Fatigue and drawing just back of the mastoids are frequently noted. Great mental depression and hypochondriasis are prone to come on. These nervous symptoms are due to "nerve leakage," resulting from the never-ceasing spurring on of the fagging convergence, and the condition may progress so far as to render single vision impossible for points within a useful working distance for any length of time.

Diagnosis

1 *Cover Test.* This test will serve to create at least a suspicion of convergence insufficiency in the mind of the examiner.

2 *Existence or Non-Existence of Heterophoria.* The usual routine test will serve to detect a condition of heterophoria. In convergence insufficiency, however, there may be apparent orthophoria, or there may be some degree of exophoria or even of *apparent* esophoria. The question arises as to the significance of an *esophoria*, which would seemingly be entirely out of place in a case of weakness of convergence. This esophoria is held to be *apparent* and not real, the convergence insufficiency being the key of the condition. "In the constant effort to maintain sufficient convergence to avoid heteronymous diplopia for the near point, a partially spastic condition of the internal recti muscles is induced, which would account for this seeming esophoria for distance. We do not consider that this spurious esophoria should be a bar to efforts to increase the positive convergence in the condition under discussion. It is a result of the insufficiency of convergence; not a definite, real state of muscle imbalance. Consequently, in our efforts to correct the insufficiency of convergence in any case, whether by prism exercises or by operative procedures, we ignore such apparent esophoria, and find invariably that it disappears after the positive convergence has been brought up to the degree required."

3 *Determination of Punctum Proximum of Convergence.* "It need not be expected that the power of convergence of the visual axes may be determined with any degree of accuracy by the use of adductive prisms, with the test object at 20 feet. I am well aware that many ophthalmologists, whom we consider as authorities, have held that healthy eyes should show upon demand a prism convergence for distance of 30°, or 35° to 50°, and that persons who cannot do this have convergence weakness. I must disagree with this dictum. Healthy eyes after training with prisms may no doubt attain this degree of adduction, but not at the first office examination in advance of such training. In 1897 I conducted a series of experiments upon the subject of the dynamics of the ocular muscles, making use of 100 healthy

young men of the regular army, who were in perfect physical condition, and who had never had a symptom referable to their eyes. Only one of these healthy young men was able to exhibit a prism convergence of 26°, the highest degree reached, the average prism adduction being 14.1°." The conclusion has previously been reached "that the determination of the punctum proximum of convergence, and the calculation of the maximum convergence, after the method of Landolt, are the only true tests of the real power of convergence, or the positive convergence."

"How much convergence should a given individual have in order that near vision may be maintained with comfort? Schuurman and Duane hold that the normal individual should see an object (as the dot) singly up to 2 1/8″ from the corneae, which would be equivalent to a maximum convergence of 18.8 metre angles. Landolt, in his great work, *The Eye*, places the necessary maximum of convergence at 9.5 metre angles. I am of the opinion that the exigencies and serious demand upon the eyes of our strenuous American life require a higher degree of convergence than that given by Landolt, while a lesser amount than the 18.8 metre angles advised by Schuurman and Duane would seem to be sufficient. In my experience 13 metre angles of positive convergence will furnish sufficient power of convergence to secure thoroughly comfortable use of the eyes in near work, and I have made this the standard in my practice. This would mean, of course, that the patient should see the test object singly at three inches from the eyes."

4 *Determination of the Punctum Remotum of Convergence.* After finding the maximum of convergence in a given case and discovering it to be insufficient, the negative convergence or abduction should be investigated in order to find what part a possible overaction of the external recti muscles may be playing. Prism abduction, unlike prism adduction, remains quite constant in healthy eyes and cannot be appreciably increased by exercises with prisms.

Treatment

(a) Any existing ametropia must be accurately corrected by lenses, and the patient be required to wear his correction constantly as an essential to success. In myopic conditions, showing moderate degrees of convergence insufficiency, this may relieve the trouble, but in marked degrees of the affection under discussion, whether in myopic or hypermetropic states, other treatment will be required as a rule. I consider prisms, bases in, combined with the ametropic correction contraindicated, and have not prescribed them for many years. The reasons for this are obvious.

(b) Training with adductive prisms and other exercises. Systematic training with adductive prisms of gradually increasing strengths, after the method of Gould of Philadelphia, may prove efficient in moderate types of convergence insufficiency.

The methods of training the adduction advocated by Worth are also highly beneficial as adjuvants in certain cases. Worth's amblyoscope I have at times found of service as a means of stimulating the fusion impulse and thus improving the innervation of the adductive muscles.

These methods may be satisfactory in instances where the maximum of convergence does not fall below 6 1/2 metre angles.

(c) Treatment by operative methods. Where the maximum of convergence is decidedly low, say about 5 or 6 metre angles, especially if the negative convergence is comparatively high, operation will be indicated in the presence of marked nervous symptoms. Under such conditions, operation should be undertaken even if there should be an apparent esophoria.

Conclusions

The conclusions drawn from the paper are:—

1 That convergence insufficiency of the type discussed in this paper is a definite pathologic entity.

2 That this state is due to lack of proper innervation of the adductor muscles, which innervation is under the control of a special cerebral center.

3 That the use of adductive prisms cannot be relied upon to furnish an estimate of the power of convergence in any given case.

4 That the power of convergence must be determined by finding the punctum proximum of convergence, and estimating the maximum convergence in meter angles.

5 That the negative convergence should be determined by abductive prisms as furnishing an important indication of a possible over-action of the external recti muscles, the normal negative convergence being about one meter angle.

6 That the normal maximum of convergence may be placed at about 13 meter angles, and that any marked falling below this standard is positive evidence of the existence of convergence insufficiency.

7 That if the maximum of convergence does not fall below 6 1/2 meter angles, exercises with adductive prisms, and other exercises, to strengthen the adduction may affect a cure of the convergence insufficiency through stimulation of the innervation.

8 That if the maximum of convergence is as low as 5 meter angles, operation will be necessary as a rule.

9 That the existence of an apparent esophoria, in the presence of a definite convergence insufficiency, is no bar to efforts to correct the latter either by exercises or by operation, as the convergence insufficiency is the key of the condition.

10 That operative measures should be of the nature of an advancement, or shortening of the internal rectus muscle, rather than a tenotomy of the antagonist, the latter expedient being reserved for rare and very extreme cases.

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